Sonoma Technology, Inc.

1360 Redwood Way, Suite C
Petaluma, CA 94954-1169
707/665-9900
FAX 707/665-9800
www.sonomatech.com

ANALYSIS OF YEAR 2000 AIR QUALITY DATA COLLECTED BY THE BAYLOR UNIVERSITY AIRCRAFT

FINAL REPORT
STI-900930-2096-FR

By:
Clinton P. MacDonald
Charley A. Knoderer
Paul T. Roberts
Martin P. Buhr
Sonoma Technology, Inc.
1360 Redwood Way, Suite C
Petaluma, CA 94954-1169

Prepared for:
Grazia Zanin
Baylor University
P.O. Box 97413
Waco, TX 76798

July 15, 2001

ACKNOWLEDGMENTS

This project was sponsored by the Texas Natural Resource Conservation Commission (TNRCC) through Baylor University with support from Ken Rosacky of TNRCC. TNRCC also sponsored the collection and processing of the air quality data collected by the Baylor University aircraft and performed by Dr. Max Shauck, Sergio Alvarez, Grazia Zanin, Monty Suffern, Joshua Begbie, Matt Tilghman, and Jimmy Flynn of Baylor University with assistance from Ken Rozacky and Bryan Lambeth of TNRCC, and Jerry Anderson and Dr. Martin Buhr of Sonoma Technology, Inc. (STI). Sergio Alvarez, Grazia Zanin, and Joshua Begbie of Baylor University produced the aircraft data plots used in this report. Curtis Reutner of TNRCC produced the hourly satellite images and supplied the radar wind profiler data to STI. Shane Motley and Duc Nguyen of STI assisted in the review of the data plots.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Section **Page**

TABLE OF CONTENTS (Concluded)

Section **Page**

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Concluded)

LIST OF TABLES

1. INTRODUCTION

1.1 OVERVIEW

During summer 2000, Baylor University staff flew a Twin Otter aircraft on 33 days (48 separate flights) collecting aloft air quality and meteorological data in Texas. Thirty-three of these flights were flown in the Houston–Galveston Bay area. The 17 remaining flights were typically flown around El Paso or Corpus Christi. An overview of the Baylor aircraft and the year 2000 flights can be found in Suffern et al., 2000. In late fall 2000, Baylor University asked Sonoma Technology, Inc. (STI) to display, describe, and characterize the air quality data collected during these flights and, in doing so, address some technical questions regarding ozone pollution in the Houston–Galveston area. Because of a limited budget, detailed characterizations of the flight data were completed for 20 selected flights. For information on the other 28 flights, see Suffern et al., 2000. This report documents this characterization and review.

1.2 TECHNICAL QUESTIONS ADDRESSED DURING CHARACTERIZATION OF THE DATA

Aloft air quality data can be used in conjunction with meteorological and emissions data to better understand the processes that influence air quality. Aloft air quality data are important because they provide information in the third dimension and spatial information between and above surface monitoring sites. To answer technical questions regarding ozone pollution in the Houston–Galveston area, aloft ozone, total reactive nitrogen (NO_y), sulfur dioxide (SO_2), and carbon monoxide (CO) concentration data were analyzed along with Continuous Air Monitoring Station (CAMS) air quality and meteorological data, satellite data, radar profiler wind and reflectivity data, emissions data, weather charts, and Eta Data Assimilation System (EDAS) data. Below are the technical questions that were addressed during the characterization of the data. Each question is followed by an explanation of why the question is important.

- **What are the general spatial and temporal characteristics of the ozone and NO_y data collected during year 2000 flights in the Houston–Galveston area?** *Understanding the spatial characteristics of the air quality provides the foundation needed to develop a more comprehensive understanding of the processes that influence ozone air quality in the Houston–Galveston area and to answer many of the subsequent questions. Additionally, this information can be used to support photochemical modeling efforts.*
- **How do the Gulf and Bay Breezes influence air quality conditions in the area surrounding Galveston Bay?** *For this analysis, flight data, radar profiler data, and other supporting data were analyzed to characterize the vertical and horizontal distribution of ozone and NO_x in the area surrounding Galveston Bay and to investigate how the Gulf and Bay Breezes relate to or influence the observed characteristics. The results from this analysis can be used to develop a revised or more comprehensive conceptual model of the Gulf and Bay Breezes influence ozone air quality in the Houston–Galveston area. In addition, the results can be used to verify that*

photochemical models replicate the important phenomena that influence ozone air quality.

- **How much does ozone stored aloft contribute to the surface ozone when aloft air mixes down to the surface during the day? Where does the aloft ozone come from? Is it yesterday's locally generated ozone, regional-background ozone, or is it from a nearby upwind point source?** *For this analysis, air quality data collected during selected morning flights, radar profiler data, and other supporting data were reviewed to determine the contribution of aloft carryover of pollutants to the peak surface ozone concentrations in the area surrounding Galveston Bay. The resulting information can be used to provide background conditions for photochemical modeling efforts and to help differentiate the contribution of local and regional sources to local peak ozone concentrations.*
- **Are some episodes attributable to specific sources or are all episodes due to the contribution of many sources?** *For this analysis, a selected number of flights were reviewed to determine the potential influence of ozone production associated with emissions in the Ship Channel area on downwind ozone concentrations. The results provide information to help us understand the different ozone episode types, that is, whether some episodes are specially related to emissions from the Ship Channel. This information can assist in the selection of ozone episodes to model and in model verification.*
- **Do correlations between ozone and other air quality variables attribute variations in ozone concentrations to different sources?** *The principal goal of the correlation analysis performed was to understand the co-variation of ozone with NO_y, indicative of the precursor NO_x, and with the primary pollutants SO_2 and CO, which can lend insight into the sources of the observed NO_x. Scatter plots of ozone vs. NO_y, ozone vs. CO, and ozone vs. SO_2 are presented in this report for each flight performed. In addition, scatter plots of SO_2 vs. NO_y and CO vs. NO_y are presented. These plots also contain lines representative of expected emission ratios from a variety of point and mobile sources, which allows a qualitative analysis of the source types that have contributed NO_x to a particular air mass. In addition, the slope between NO_y and ozone was used as a qualitative measure of aloft ozone production efficiency per emitted NO_x.*
- **How does the aircraft wind data compare with the wind data collected by the Ellington Field radar wind profiler?** *The Baylor aircraft collected wind data during all flights. Before using this data in analyses, it is important to know if the data accurately represents the winds as indicated by other measurement devices.*

1.3 REPORT ORGANIZATION

The report is organized as follows:

- Section 2 summarizes the general findings from the data analyses.
- Section 3 discusses the data availability and data sources used in the analyses.

- Section 4 discusses the data plots used in the analysis and how they were used to characterize the air quality data collected by the aircraft.
- Section 5 presents a detailed characterization and analysis of air quality and meteorological data collected during 20 flights in the Houston–Galveston area.
- Section 6 presents pollution rose plots and a comparison of the wind data collected by the aircraft and radar profiler wind data collected at Ellington Field, Houston.
- Section 7 discusses correlations of ozone and SO_2, ozone and NO_y, ozone and CO, SO_2 and NO_y, and CO and NO_y. Section 7 also explores ozone production efficiency.
- Section 8 presents recommendations for future analyses.

2. FINDINGS

This section reports our findings based on review of the aloft air quality data collected by the Baylor University aircraft on 20 selected flights during the summer of 2000; surface meteorological and air quality data; upper-air meteorological data; and Eta model output. These findings are part of the underpinnings of a conceptual model of the important phenomena that produce high ozone concentrations in the Houston–Galveston Bay area. Perhaps the most useful application of these findings will be to support three-dimensional photochemical modeling used to develop emission control strategies. Refer to the appropriate report sections as noted below for the details from which these findings were drawn. Note that many of the findings presented in this section are summarized in **Table 2-1**.

Usefulness of Aircraft Data (Sections 4 though 7)

The air quality data collected by the Baylor University aircraft are useful for understanding the three-dimensional distribution and characteristics of ozone, NO_y, NO, and SO_2 in the Houston–Galveston Bay area. Aloft data are essential to understanding the contributions of transported pollutants and the distribution of pollutants within the boundary layer.

Meteorology and Transport (Section 5)

An aloft high-pressure system influenced weather in Houston on 11 of 12 high ozone flight days when the Baylor aircraft collected air quality data in and around the Houston–Galveston Bay area. At the surface, the behavior of large-scale pressure gradients played an important role in the local flow pattern.

Regionally, the aloft high-pressure systems were characterized by limited vertical mixing, clear skies, and relatively light winds aloft. Locally, peak mixing heights on 10 flight days with available radar wind profiler data ranged from approximately 5904 to 12,136 ft msl (1800 to 3700 m msl), averaging 7544 ft msl (2300 m msl). These peak mixing heights and their diurnal patterns should be replicated in photochemical modeling efforts.

Unlike in other areas of Texas, high regional-background ozone concentrations (70 to 80 ppb) associated with a sustained aloft high pressure system (MacDonald et al., 2000) were not observed in the Houston–Galveston Bay area where aloft (above the morning boundary layer, about 1968 ft msl [600 m msl]) ozone concentrations ranged from approximately 30 to 70 ppb. This means that the high peak surface ozone concentrations observed in the Houston–Galveston Bay area are primarily locally generated.

Twenty-four hour Eta Data Assimilation System (EDAS) back-trajectories indicate that the aloft morning background ozone concentrations originated over the Gulf of Mexico on five of the seven days with morning aloft data. On these five days, aloft ozone concentrations ranged from 30 to 70 ppb. On one other day (August 30, 2000), the aloft air originated near Corpus Christi and the aloft ozone concentrations were 70 ppb. On another day (September 1, 2000), the aloft air originated near Houston and the aloft ozone concentrations were 60 ppb. Aloft morning

NO_y concentrations above 1968 ft msl (~600 m msl) ranged from 0 to 5 ppb, and were highest on August 30, 2000, when the air originated near Corpus Christi. Aloft morning NO and SO_2 concentrations above 1968 ft msl (~600 m msl) were usually below the detection limit (~0 ppb).

Locally, aloft high-pressure systems and, on some days, weak large-scale surface pressure gradients allowed for the land/sea breeze circulation in the Houston–Galveston area to occur. However, on other days, when a large-scale surface pressure gradient was present, the land/sea breeze circulation did not occur. Modeling of any given day needs to accurately replicate the observed flows. The frequency of occurrence of these flows and associated peak ozone concentrations are as follows:

- On 4 of the 11 flights days with available data, there was land/sea breeze circulation. On these days, the onshore southerly flow was typically observed throughout the night and midmorning hours. By late morning, the wind would turn offshore (northerly). By early afternoon, a southeasterly Bay Breeze would begin and by mid-afternoon a southerly Gulf Breeze would begin and last through the evening. Peak surface and aloft ozone concentrations on the land/sea breeze days were generally the highest of all flow day types. On these days, peak ozone concentrations occurred near the Ship Channel close to Baytown or La Porte, or in central Houston.
- On 3 of the 11 flights days, an onshore (sea breeze) flow was present throughout the day. On these days, peak ozone concentrations occurred north of Baytown or north of Houston.
- On 2 of the 11 days, there was westerly flow, and peak ozone concentrations occurred near Baytown.
- On 1 day, there was northerly flow the entire day, and the peak ozone concentrations occurred on the Gulf Coast near Clute.
- On 1 day, there was southeasterly and easterly flow the entire day, and peak ozone concentrations were low (100 ppb at the surface and 110 ppb aloft) and occurred near central Houston and north of Houston.

General Spatial and Temporal Characteristics of the Observed Ozone and NO_x (Section 5)

Understanding the spatial characteristics of the air quality data provides the foundation needed to develop a more comprehensive understanding of the processes that influence ozone air quality in the Houston–Galveston Bay area, and these characteristics need to be replicated in photochemical modeling efforts. Both morning and afternoon aircraft flights revealed consistent, yet complex three-dimensional structure. Much of the data used in this analysis were collected during box climbs, the circling or boxing of the aircraft around a fixed point while ascending or descending a few thousand feet or more. The radius of each box climb was about 6 km. In general, the morning flight data show the following:

- As mentioned above, aloft morning ozone concentrations above approximately 2000 ft msl and below the maximum height of the afternoon mixed layer (about 5000 ft msl) ranged from 30 to 70 ppb. In this layer, NO_y concentrations were typically 3 ppb and ranged from 0 to 5 ppb. NO and SO_2 concentrations were very low.

- Below 1000 ft msl, early morning ozone concentrations throughout Houston and Galveston Bay were titrated and ranged from near 0 to 30 ppb.
- Within the lowest 2000 ft msl and within the morning boundary layer, the box climbs showed that there were typically two to three different layers of pollutants with varying characteristics and one or two temperature inversions. Since these layers are entrained into the daytime boundary layer, it is important that modeling efforts produce layers similar to those observed by the aircraft. The typical characteristics of these layers are as follows:
  - In the lower layers, usually from 250 to 1000 ft msl, ozone concentrations were titrated and typically lower than 30 ppb. Collocated NO_y concentrations were typically 10 to 30 ppb, but, at times, were as high as 170 ppb. NO concentrations in these lower layers were typically from 0 to 10 ppb, but were, at times, as high as 90 ppb (e.g., the September 12 La Porte box climb). SO_2 concentrations typically ranged from near 0 to 15 ppb.
  - Between approximately 1000 and 2000 ft msl, ozone concentrations were typically 30 ppb. Collocated NO_y concentrations typically ranged from 2 to 30 ppb and NO concentrations were usually near 0 ppb. SO_2 concentrations were usually near 0, but on a few box climbs were as high as 70 ppb (e.g., the August 30 La Porte box climb).

In general, the afternoon flight data show the following characteristics:

- Peak aloft ozone concentrations generally occurred near the Ship Channel, near Baytown, or in Central Houston.
- The peak aloft ozone concentrations ranged from 100 ppb on September 4 to 205 ppb on August 25.
- With the exception of August 30 and September 3, the peak aloft ozone concentrations were generally similar to the peak surface ozone concentrations.
- On every day analyzed, SO_2 concentrations from 5 to 20 ppb were observed at the time and location of the peak ozone concentrations. Collocated NO_y concentrations were 5 to 25 ppb. Therefore, it is probable that NO_x point source plumes that also emit SO_2 contributed to the peak ozone concentrations. For example, on the afternoon of August 19, from 1800 to 3200 ft msl (550 to 976 m msl) there was an aloft layer with SO_2 up to 10 ppb, NO_y up to 5 ppb, and ozone up to 115 ppb, but little NO. The 700-m (2296-ft) trajectory indicated that air at this altitude probably originated from over Texas City in the morning around 0800 or 0900 CST, and this southerly flow was associated with the Gulf Breeze.
- Over Galveston Bay in the afternoon (the location of the vertical box climb), pollutant concentrations vary considerably with elevation and between days. This box climb usually occurred from about 1500 ft msl to about 6000 ft msl. On several days, more than one of the layers described below existed during the same box climb at different levels.

- On some days there were layers that contained high NO_y and NO concentrations and titrated ozone. Some of these layers contained high SO_2 concentrations (for example, August 19) and some of these layers contained little SO_2 (for example, August 18). These layers were probably formed from fresh emissions.
- On some days there were layers that contained high NO_y and ozone concentrations. Some of these layers contained high SO_2 concentrations (for example, September 3) and some of these layers contained little SO_2 (for example, August 19). These layers were probably aged emissions.
- On some days almost the entire box climb was one layer that was probably background air since it contained little SO_2, NO_y, and NO; ozone concentrations were from 50 to 70 ppb (for example, August 26).

Contribution to the Peak Ozone Concentrations (Sections 5 and 7)

The highest ozone concentrations generally occurred downwind of the Ship Channel area; however, trajectories indicate that the air circulation usually caused emissions from central Houston to combine with Ship Channel emissions to produce the peak ozone concentrations. The peak ozone concentrations were usually associated with SO_2 concentrations above 5 ppb. This indicates that some of the ozone is probably associated with point source NO_x emissions that also emit SO_2. Correlation among ozone and CO, SO_2, and NO_y concentrations suggest that both point and mobile sources contributed to the ozone concentrations. Analysis results of observed and expected emissions ratios were consistent with both point and mobile sources contributing significant NO_x to the air parcels observed in all but one of the flights (September 5).

Ozone Production Efficiency (Section 7)

The slope observed between ozone and NO_y was used as a qualitative measure of the ozone production efficiency per unit of emitted NO_x for those flights where photochemical production of ozone was evidenced by a correlation between ozone and NO_y. Evidence of photochemical ozone production was observed on all of the afternoon flights and some of the morning flights, with production rates ranging from 3 to 10 ppbv ozone per ppbv NO_y. The results are similar to those found in MacDonald et al., 2000.

Lower ozone production rates were associated with air that contained high SO_2 concentrations. The high SO_2 concentrations were probably associated with certain point sources.

Comparison of Aircraft Wind Data and Profiler Wind Data (Section 6)

Validated radar profiler wind data collected at Ellington Field were compared to wind data collected by the Baylor aircraft to check the quality of the aircraft wind data. The calculations show that the wind directions observed by the aircraft contain a bias of -17.9º and a root mean square difference (uncertainty) of 49.1º when compared to the radar profiler wind direction data. The calculations also show that the wind speeds had a bias of -0.6 knots and a rather high uncertainty of 4.2 knots. In some cases, the aircraft wind data compare well with the radar profiler wind data, such as the Galveston Bay spiral on August 19, 2000. However, the aircraft wind data more often compare poorly with the radar profiler wind data. The wind data as measured by the aircraft showed a high level of uncertainty; therefore, the data cannot be used confidently without further detailed validation.

Pollution Rose Plots (Section 6)

Pollution rose plots for specific layers were created using averaged radar profiler wind data and average aircraft ozone data collected during the morning and afternoon box climbs. The morning layers were 1000 to 2000 ft msl and 2000 to 5000 ft msl. The afternoon layer was 1000 to 5000 ft msl. The following observations were made from these pollution roses:

- The pollution rose plots for the 1000- to 2000-ft msl morning box climbs show that winds were from the west or southwest on each morning except one (August 22) when east winds were observed. The ozone concentrations varied from 15 to 69 ppb from day to day. Within each day, ozone concentrations were similar among the box climbs.
- The pollution rose plot for the 2000- to 5000-ft msl morning box climb east of Texas City shows wind directions ranging from the southwest to southeast. The plot shows that ozone concentrations in this layer were typically about 50 to 70 ppb, generally greater than the ozone concentrations for the 1000- to 2000-ft msl box climb.
- The pollution rose plot for the 1000- to 5000-ft msl afternoon box climb east of Texas City shows wind directions ranging from northwest through south to east, which are more variable than during the morning. During the afternoon, ozone concentrations were 52 to 79 ppb. However, these average layer concentrations are much lower than the peak ozone concentrations observed by the aircraft on any of the days analyzed.

Final Note

The Baylor University aircraft collected a wealth of useful aloft air quality data during the summer and fall of 2000. Review of these data produced several interesting findings as presented above. These findings and much of the data presented in this report should be used to support and improve three-dimensional photochemical modeling and to further refine the conceptual model of ozone formation in the Houston–Galveston Bay area. In addition to using the findings discussed in this report, it is recommended that any modeling effort of summer 2000 flight days contain a component that utilizes all of the aircraft data delivered to the Texas Natural Resource Conservation Commission by Baylor University.

Table 2-1. Summary of air quality and meteorology during selected Baylor aircraft flights in the Houston-Galveston Bay area.

Date	Flight No.	Time of Day	Morning Aloft Background Ozone Conc. (ppb)	Morning Aloft Background NO_y Conc. (ppb)	Morning Aloft Background NO Conc. (ppb)	Morning Aloft Background SO_2 Conc. (ppb)	Aloft Background Origination Point from Prior Day	Afternoon Peak Surface Ozone Conc. (ppb)	Time of Afternoon Peak Surface Ozone Conc. (CST)	General Location of Afternoon Peak Surface Ozone Conc.	Peak Aloft Ozone Conc. (ppb)	Time of Peak Aloft Ozone Conc. (CST)	General Location of Peak Aloft Ozone Conc.	Collocated Aloft NO_y Conc. (ppb)	Collocated Aloft SO_2 Conc. (ppb)	Local Wind Pattern	Peak Mixing Height (m msl)	Time of Peak Mixing Height (CST)
08/18/00	135	Afternoon						111	1500	North Houston	115	1430	Galveston Bay	8	12	Sea breeze	1800	1300
08/19/00	136a	Morning	60-70	3	~0	0	Gulf of Mexico											
08/19/00	136b	Afternoon						146	1100	North of Baytown	140	1238	North of Baytown	10	5	Sea breeze	2000	1300
08/21/00	137a	Morning	60-70	3	0-1	0-2	Gulf of Mexico											
08/21/00	137b	Afternoon						159	1300	Central Houston	180	1340	Central Houston	25	15	Land/sea breeze	1600	1230
08/25/00	140	Afternoon						194	1300	Central Houston	205	1320	Ship Channel area	N/A	20	Land/sea breeze	2000	1130
08/26/00	141a	Morning	30-40	0	0	0	Gulf of Mexico											
08/26/00	141b	Afternoon						119	1100	North of Baytown	115	1340	Ship Channel area	10	5	Sea breeze	2200	1330
08/29/00	143a	Morning	30-55	0-3	0-2	0	Gulf of Mexico											
08/29/00	143b	Afternoon						145	1500	North of Baytown	180	1340	Ship Channel area	25	10-20	Land/sea breeze	N/A	N/A
08/30/00	144a	Morning	60	2-3	1-2	0	Near Houston											
08/30/00	144b	Afternoon						195	1600	La Porte	120	1400	South-southwest of Ship Channel	15	5	Land/sea breeze	2000	1600
09/01/00	145a	Late Morning	70	5	0	0	Near Corpus Christi											
09/01/00	145b	Afternoon						160	1300	Baytown	135	1450	Baytown	20	5	Synoptic Westerly	2800	1600
09/03/00	146	Mid-day						127	1600	Baytown	180	1220	Galveston Bay	15	5	Synoptic Westerly	2500	1630
09/04/00	147a	Late Morning																
09/04/00	147b	Afternoon						115	1600	Port Arthur	100	1540	Port Arthur	N/A	N/A	N/A	N/A	N/A
09/05/00	148	Afternoon						185	1400	Clute	190	1517	Clute	25	5	Land breeze	3700	1530
09/12/00	150a	Morning	30	2	0	0	Gulf of Mexico											
09/12/00	150b	Afternoon						100	1200	North Houston	110	1340	Central Houston	25	10	South-easterly	2800	1130

3. DATA AVAILABILITY

The Baylor University's Twin Otter aircraft (see **Figure 3-1**) was outfitted with a variety of instruments for continuously measuring ozone, SO_2, sulfates, NO_y, particulate matter, temperature, and wind data, in addition to routine measurements of volatile organic compounds (VOCs). As shown in **Table 3-1**, the aircraft collected these data for 48 flights during summer and fall of 2000.

The aircraft data were processed by Baylor University. Baylor University created both spatial and time series plots of selected data for all flight days; the plots and data were supplied in electronic format to STI and the Texas Natural Resource Conservation Commission (TNRCC). The plots contain both ambient and calibration data. STI staff altered a small number of the plots for this report.

To address the technical questions listed in Section 1, the aircraft data are most useful in the context of regional emissions, air quality, and meteorological data. In this review, aloft air quality data, emissions data, surface air quality data, and surface and aloft meteorological data were examined for 20 selected flights. The sources of these additional data are as follows:

- 1997 through 1999 CAMS air quality and metrological data were obtained from TNRCC Lockheed Environmental Analysis and Display System (LEADS). The locations of the CAMS sites are shown in **Figures 3-2 and 3-3**.
- Back-trajectories were produced for selected flight days using the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) HYSPLIT4 trajectory model. Data used in the model were the EDAS data. Information about these data sets can be found at <http://www.arl.noaa.gov/ss/transport/archives.html>.
- Hourly wind data and back-trajectories were plotted for selected flight days using data collected by a radar wind profiler located at Ellington Field in Houston. Radar wind profilers measure half-hourly vertical profiles of wind up to 4000 m agl at 60- to 100-m intervals. The radar wind profiler data were supplied by TNRCC.
- Hourly daytime mixing heights were estimated from profiler reflectivity data (C_n^2 data) for 11 selected flight days using data collected by the Ellington Field radar wind profiler. The radar wind profiler C_n^2 data were supplied by TNRCC.
- Hourly visible satellite images were supplied by TNRCC.
- NOAA's National Weather Service synoptic weather charts were analyzed for selected flight days.

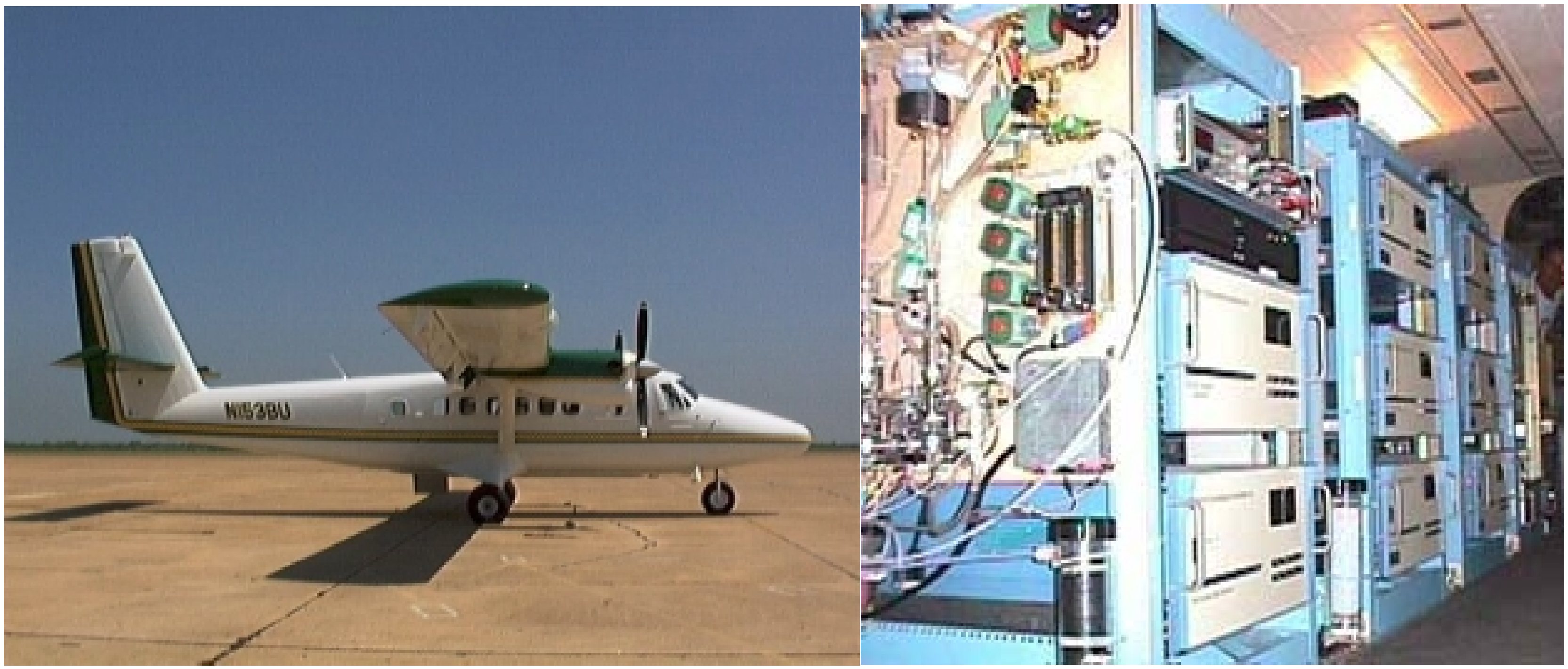


Figure 3-1. Baylor University's Twin Otter aircraft (left) and the air quality instrumentation inside Baylor University's aircraft used to measure ozone, SO_2, NO_y, particulate matter, sulfates, VOCs, wind and temperature data (right).

Table 3-1. Baylor aircraft flight summary for year 2000 flights. This table is courtesy of Suffern et al., 2000. Flights in bold text were analyzed in greater detail.

Page 1 of 2

Flight Number	Date	Main Location	Primary Objective
131	05/10/00	Corpus Christi	Shake down flight to ensure flight readiness
132	08/08/00	Waco - Houston	Instrument test and aircraft repositioning to Ellington Field, Houston
133	08/10/00	Houston	Instrument testing
134	08/16/00	Houston	AM Characterization of Early Morning Pollutants
135	**08/18/00**	**Houston**	**PM Characterization of Bay Breeze**
136 a	**08/19/00**	**Houston**	**AM Characterization of Early Morning Pollutants**
136 b	**08/19/00**	**Houston**	**PM Characterization of Bay Breeze**
137 a	**08/21/00**	**Houston**	**AM Characterization of Early Morning Pollutants**
137 b	**08/21/00**	**Houston**	**PM Characterization of Bay Breeze**
138	08/22/00	Houston	AM Characterization of Early Morning Pollutants
139	08/24/00	Houston	Media Flight
140	**08/25/00**	**Houston**	**Inter-comparison flight with G1 and Electra**
141 a	**08/26/00**	**Houston**	**AM Characterization of Early Morning Pollutants**
141 b	**08/26/00**	**Houston**	**PM Characterization of Bay Breeze – first flight on modified plan**
142 a	08/28/00	Houston	AM Characterization of midmorning bay breeze onset
142 b	08/28/00	Houston	PM Media Relations Flight
143 a	**08/29/00**	**Houston**	**AM Characterization of Early Morning Pollutants**
143 b	**08/29/00**	**Houston**	**PM Characterization of Bay Breeze**
144 a	**08/30/00**	**Houston**	**AM Characterization of Early Morning Pollutants**
144 b	**08/30/00**	**Houston**	**PM Characterization of Bay Breeze**
145 a	**09/01/00**	**Houston**	**AM midmorning characterization of ozone vertical plume**
145 b	**09/01/00**	**Houston**	**PM afternoon characterization of ozone vertical plume**
146	**09/03/00**	**Houston**	**Inter-comparison flight and plume characterization**
147 a	**09/04/00**	**Houston**	**AM Characterization of Beaumont plume**
147 b	**09/04/00**	**Houston**	**PM Characterization of Beaumont plume**
148	**09/05/00**	**Houston**	**Characterization of afternoon land breeze in urban plume**
149	09/07/00	Houston	Characterization of afternoon land breeze in urban plume
150 a	**09 12/00**	**Houston**	**AM Characterization of Early Morning Pollutants**
150 b	**09/12/00**	**Houston**	**PM Characterization of Bay Breeze**
151	09/14/00	Houston	Point source sampling
152	09//15/00	Houston	Urban plume study – source characterization over Galveston bay
153 a	09/28/00	Regional flight	Characterization of regional plume – Waco to Victoria, TX
153 b	09/28/00	Regional	Characterization of regional plume – Victoria to Corpus Christi, TX
153	09/28/00	Corpus Christi	Characterization of regional plume around Corpus Christi
154 a	09/29/00	Corpus Christi	AM Characterization of regional plume around Corpus Christi
154 b	09/29/00	Corpus Christi	PM Characterization of regional plume around Corpus Christi
155 a	09/30/00	Regional	Characterization of regional plume – Corpus Christi to San Antonio
155 b	09/30/00	Regional	Characterization of regional plume – San Antonio to Waco
156 a	10/04/00	Waco/Houston	Study of Parish Power Plant plume
156 b	10/04/00	Houston/Waco	Houston urban plume characterization
157	11/19/00	El Paso	Characterization of high CO levels on Border near El Paso

Flights with the letter "a" after the flight number are morning flights, and flights with the letter "b" after the flight number are afternoon flights. Flights with no letter are generally midday flights.

Table 3-1. Baylor aircraft flight summary for year 2000 flights. This table is courtesy of Suffern et al., 2000. Flights in bold text were analyzed in greater detail.

Page 2 of 2

Flight Number	Date	Main Location	Primary Objective
158 a	11/20/00	El Paso	AM Characterization of high CO levels on Border near El Paso
158 b	11/20/00	El Paso	PM Characterization of high CO levels on Border near El Paso
159 a	11/21/00	El Paso	AM Characterization of high CO levels on Border near El Paso
159 b	11/21/00	El Paso	PM Characterization of high CO levels on Border near El Paso
160	12/04/00	El Paso	Characterization of high CO levels on Border near El Paso
161	12/05/00	El Paso	Characterization of high CO levels on Border near El Paso
162	12/06/00	El Paso	Characterization of high CO levels on Border near El Paso

Flights with the letter "a" after the flight number are morning flights, and flights with the letter "b" after the flight number are afternoon flights. Flights with no letter are generally midday flights.

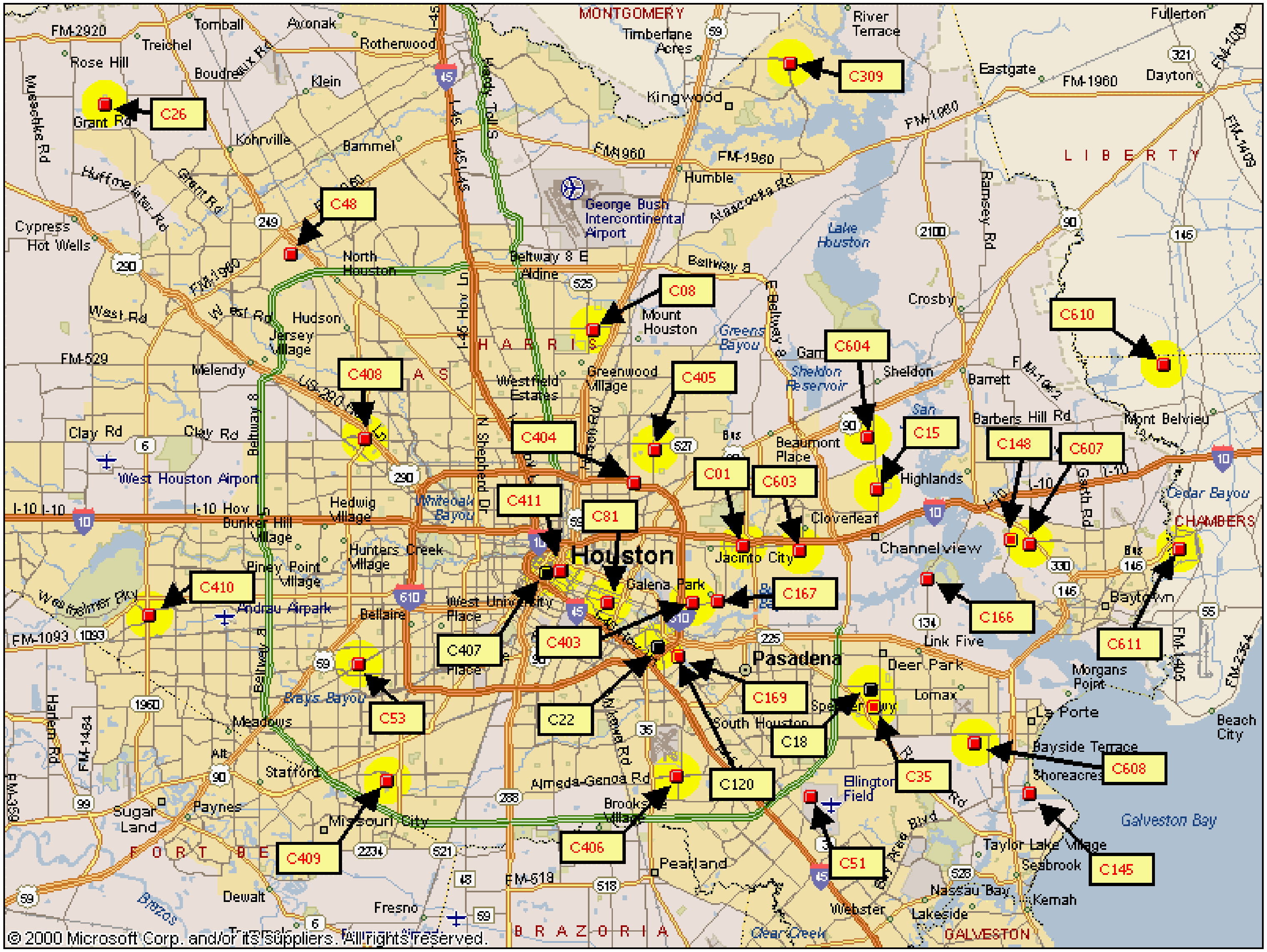


Figure 3-2. CAMS surface monitoring sites in the Houston–Galveston Bay region. Figure is from TNRCC LEADS.

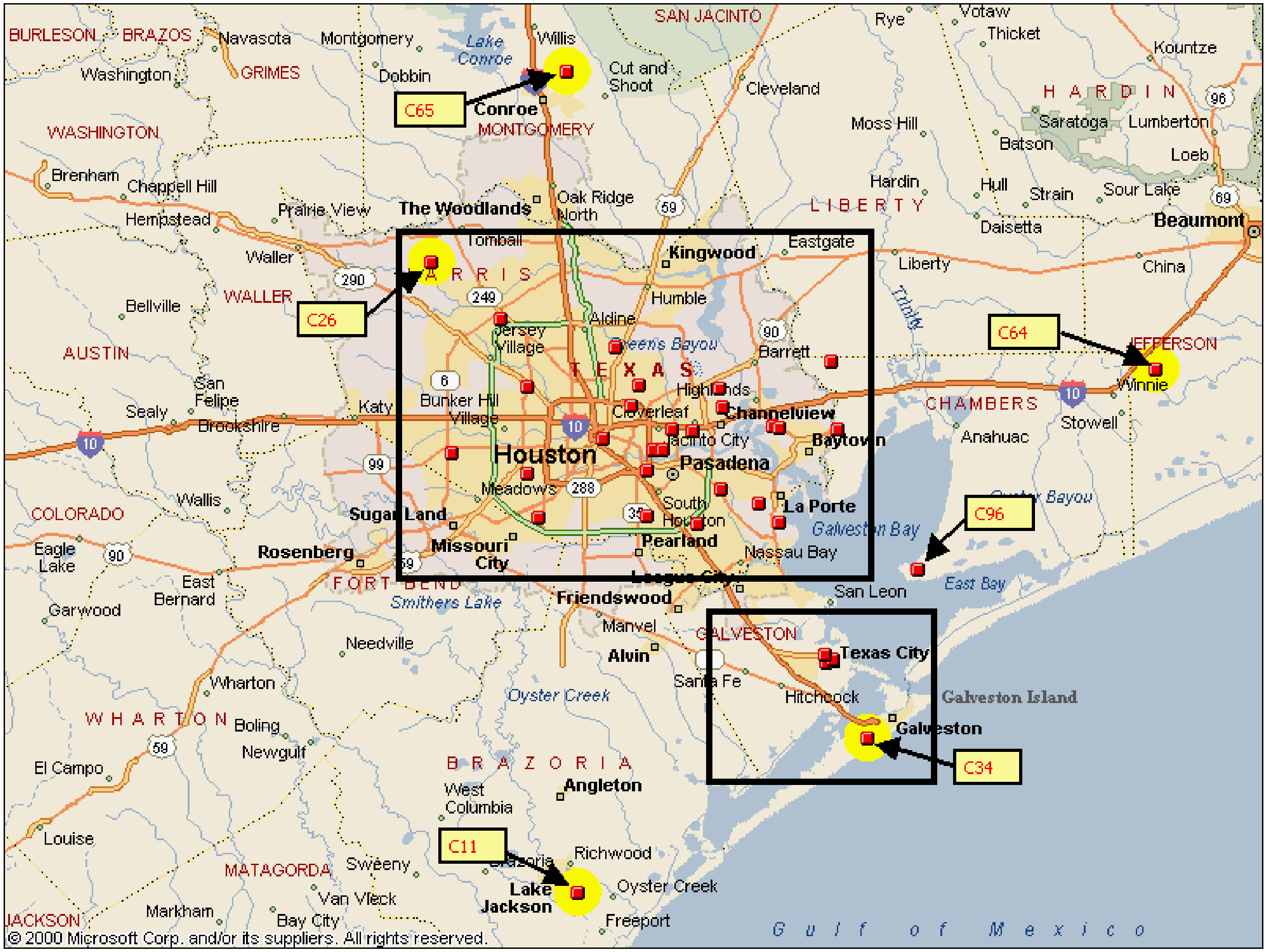


Figure 3-3. CAMS surface monitoring sites in the greater Houston–Galveston Bay region. Figure is from TNRCC LEADS.

4. DATA DISPLAY AND REVIEW METHODS

4.1 PURPOSE

The main purpose of the data review was to characterize the air quality data collected during Baylor University's year 2000 flights, and to address some specific technical questions regarding air pollution in the Houston–Galveston area. In this report section, we provide examples of some of the plots that we used and explain how they were interpreted. These types of plots and similar interpretations appear extensively in the remainder of the report.

4.2 SPATIAL PLOTS OF AIR QUALITY DATA

Spatial plots of ambient and calibration ozone, NO_y, and SO_2 data were produced by Baylor University and were used to characterize the data collected during each of the flights. **Figure 4-1** is a sample of such a plot and it shows ozone data collected on Flight 135 on the afternoon of August 18, 2000. The multicolored line shows the flight path. The internal color of the line indicates the ozone concentration (ppb) as described in the ozone legend in the bottom left corner of the plot. Bounding the flight path line are gray-scale lines, which indicate the altitude of the aircraft (457 m msl). Knowing the altitude of the aircraft is important because apparent changes in the horizontal ozone concentrations may actually be changes in the vertical ozone concentrations due to changes in the aircraft's altitude rather than changes in the aircraft's horizontal position. On most plots, black arrows alongside the flight path indicate the direction the aircraft was traveling. Various points of interest are also displayed on the plots. For example, takeoff and landing locations and times and box climbs are shown. A box climb, the ascent or descent of an aircraft while circling (or boxing) about a point, is used to determine the vertical pollutant structure in a finite area. In Figure 4-1, a box climb over Galveston Bay began at about 1430 CST on August 18, 2000. During the box climb, ozone concentrations ranged from approximately 45 ppb at 2800 ft msl (854 m msl) to 115 ppb at 1500 ft msl (457 m msl). The figure also shows the surface ozone concentrations and the time of the measurement (begin hour CST) for sites and the times shown were selected to coincide with the time that the aircraft flew by the site. The peak surface ozone reading within the time of the aircraft flight is also shown. On some plots, blue circles indicate the locations of point source NO_x emissions. The size of a circle indicates the NO_x source strength, and the source strength is scaled by the area of the circle. Finally, the metropolitan areas are shaded on the plot.

4.3 BACK-TRAJECTORIES

For selected flights, back-trajectories and wind runs were overlaid on the spatial plots. 140-m, 700-m, and 1500-m agl back-trajectories were created using NOAA ARL's HYSPLIT 4 trajectory model with EDAS data. 140-m, 700-m, and 1500-m agl wind runs were created using Ellington Field radar profiler wind data. These are called wind runs because the profiler wind data are measured at one point in space. However, in the remainder of the report, the profiler wind runs are referred to as back-trajectories. These back-trajectories were used to estimate the paths of air parcels and indicate possible sources of emissions that contribute to the peak ozone concentration. The three levels were chosen to capture the different wind flows that can occur at various heights within the daytime mixing layer. The back-trajectories were run from the time of peak ozone concentration as measured by the aircraft back to 0500 CST on the same day. The EDAS back-trajectories were run back from Ellington Field and the profiler back-trajectories were run back from the location of peak aloft ozone concentrations as measured by the aircraft. A sample of a back-trajectory plot overlaid on ozone data is presented in Figure 4-1. Twenty-four-hour EDAS back-trajectories were also created to determine where the air came from the day prior. It is important to note that because of the course grid resolution of the EDAS data (40 km) and because the profiler data may not be spatially representative, neither the EDAS nor profiler back-trajectories represent the exact parcel movement. However, the back-trajectories can be used as an indication of the general direction and distance that the air parcels traveled.

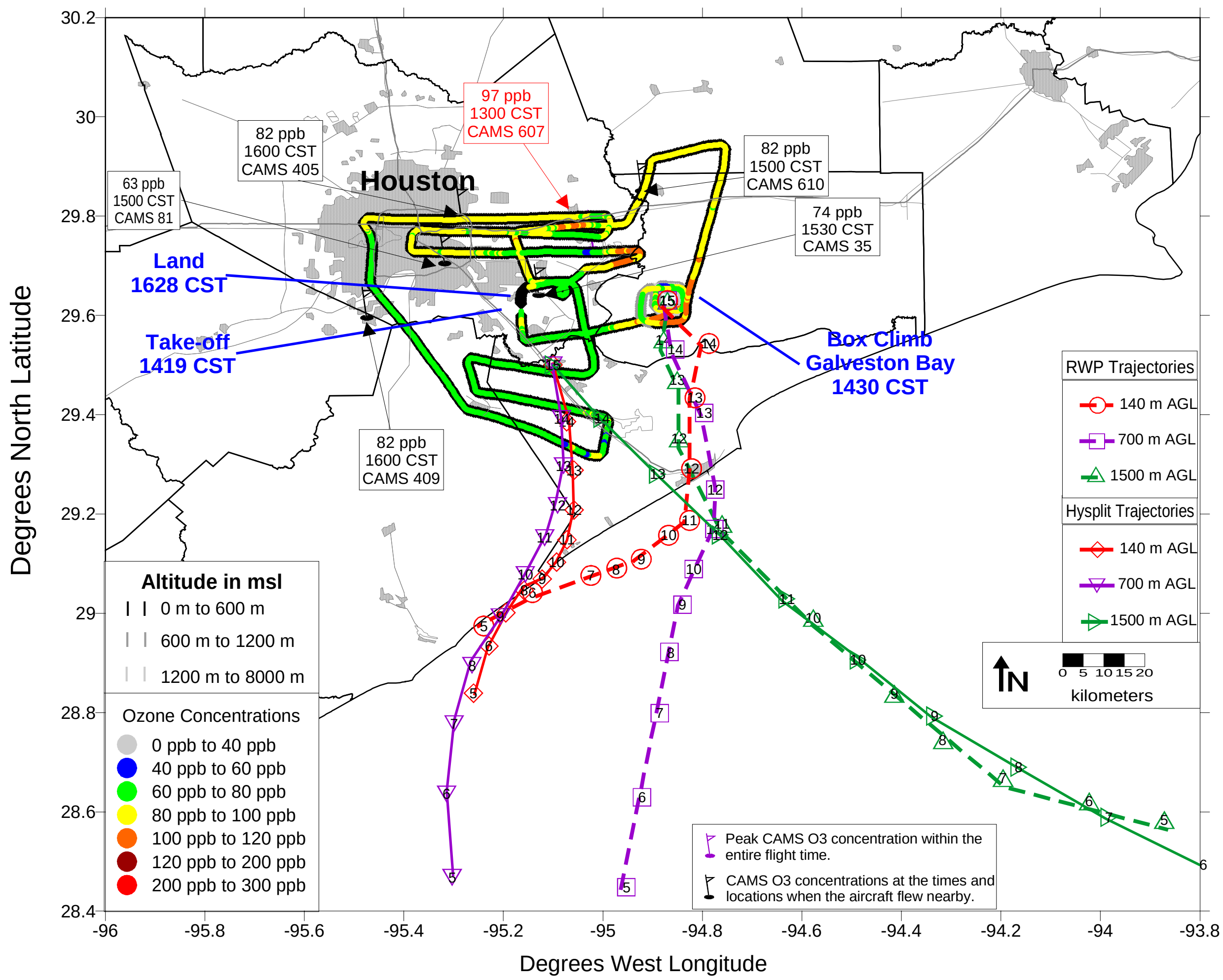


Figure 4-1. Flight 135 flight position, altitude, aloft ozone concentrations, CAMS surface ozone concentrations, and back-trajectories on the afternoon of August 18, 2000.

4.4 TIME SERIES AND VERTICAL PROFILE PLOTS

Time series and vertical profile plots of the air quality and temperature data (ozone, NO, NO_y, NO_y*, SO_2, SO_4, CO, and nephelometer) were created by Baylor University and delivered to STI. Note that NO_y* data, although included in the plots, are considered suspect because the instrument used had a particularly high background that was not accounted for with the synthetic zero air test. In addition to ambient data, the plots contain calibration data. Surface time-series plots of air quality and meteorological data collected at selected CAMS sites were created by STI. These plots were used in the review to help characterize the air quality data collecting during the flights. An example of a vertical profile of aircraft data is shown in **Figure 4-2**. The data shown in Figure 4-2 were collected from 1429 to 1436 CST on August 19, 2000. The portion of the profile shown is from approximately 1500 to 5000 ft msl. Some observations noted in this profile, typical of the observations noted in many vertical profiles, include

- Ozone, NO, and NO_y concentrations over Galveston Bay vary considerably with altitude with several distinct layers.
- At 1700 ft, there was a layer of SO_2 (15 ppb) and NO_y (5 to 10 ppb), yet very little NO (0 to 1 ppb). At this point, ozone concentrations peaked at 115 ppb.
- Between 2800 and 4000 ft msl, there was another layer; this layer contained little SO_2 but had peak NO concentrations of 12 ppb and peak NO_y concentrations of 40 ppb. Instead of ozone production, the NO had titrated ozone and ozone concentrations dropped to 45 ppb at 3000 ft msl.
- Between 4000 and 4700 ft msl, ozone concentrations increased to 87 ppb. From 4700 to 5000 ft msl, there was a temperature inversion where ozone concentrations were about 70 to 80 ppb. The aircraft did not fly higher than 5000 ft msl.

4.5 RADAR PROFILER WIND DATA

Time-height profiles of half-hourly radar profiler wind data collected at Ellington Field were plotted for selected flight days. These plots were used to characterize the different flow regimes and to determine the depth and timing of the Bay and Gulf Breezes and their relationship to the air quality data. Note that the profiler elevation is only 10 m above msl so the difference between agl and msl is small. **Figure 4-3** shows an example plot of the winds on August 25, 2000. On this day, the winds were generally north in the lowest 500 m msl between 0600 and 1200 CST. At about 1200 CST, the winds shift more easterly (the onset of the Bay Breeze) and southeasterly at 1630 CST (the onset of the Gulf Breeze).

4.6 SATELLITE DATA

In addition to using the radar profiler data to characterize the Bay and Gulf Breezes, hourly visible satellite data were reviewed to pick out the onset and progression of these breezes. For example, as shown in **Figure 4-4**, on August 19, 2000, visible satellite imagery showed the location of the Gulf Breeze front at 1209 CST (1809 UTC).

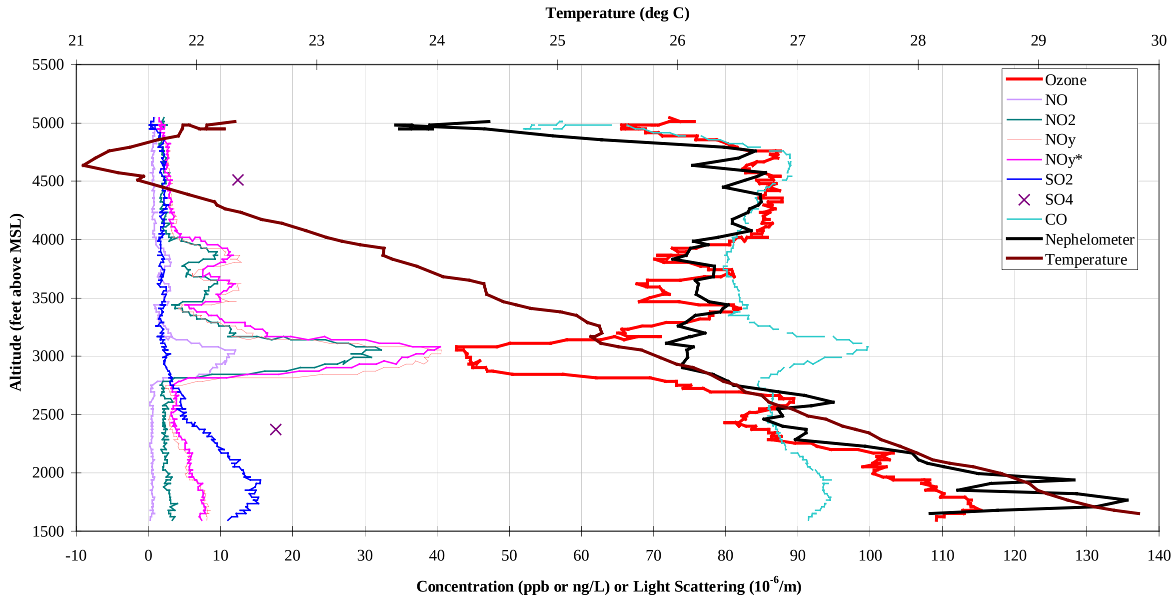


Figure 4-2. Aloft air quality data and temperature data collected from 1429 to 1436 CST on August 19.

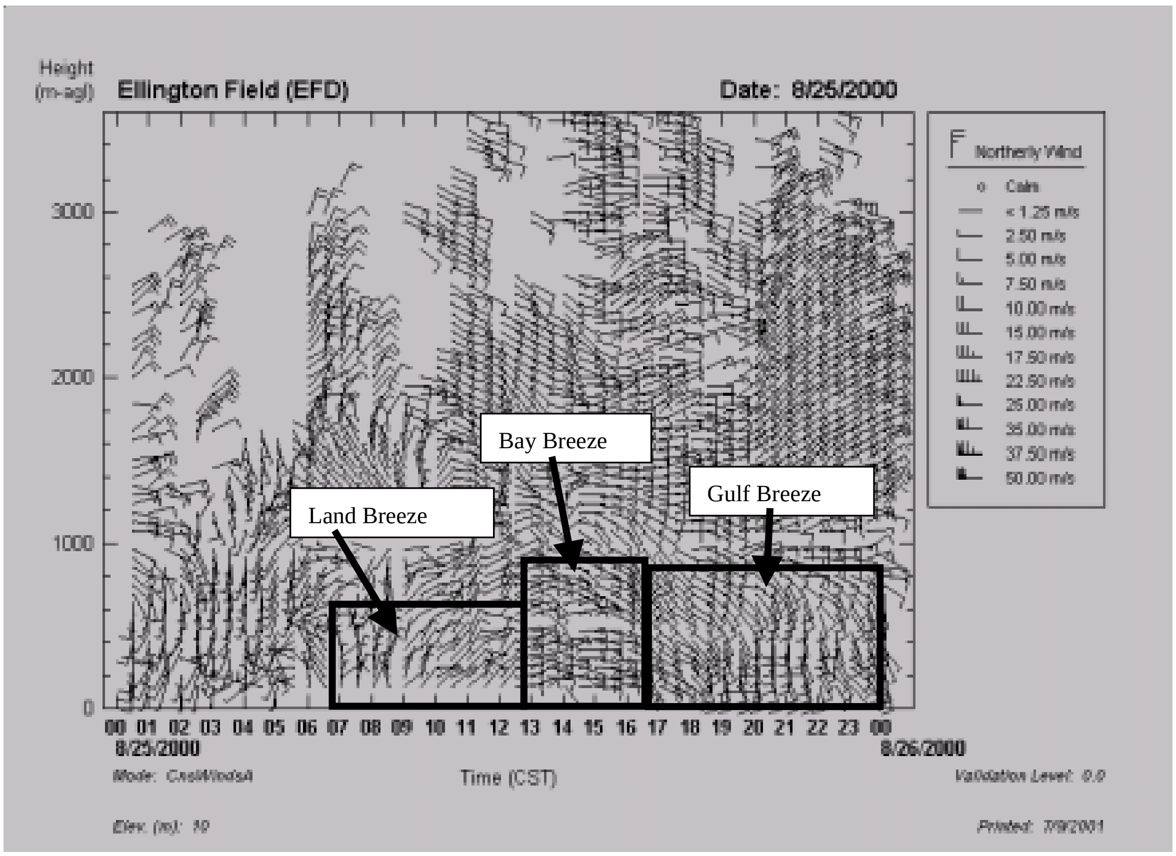


Figure 4-3. Radar wind profiler data for August 25, 2000, at Ellington Field, Houston.

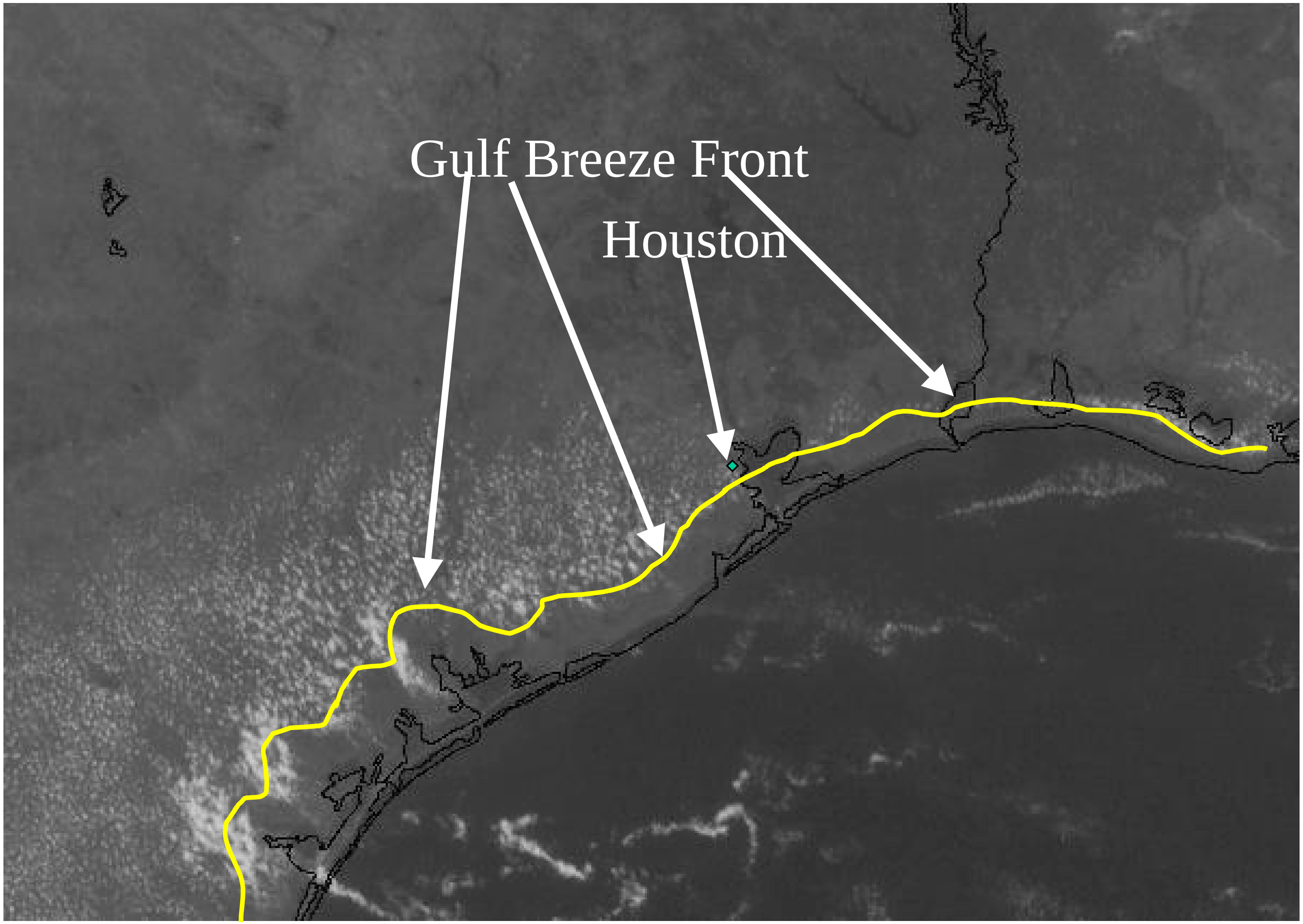


Figure 4-4. Visible satellite image of Southeast Texas at 1209 CST (1809 UTC) on August 19, 2000.

4.7 RADAR PROFILER REFLECTIVITY DATA

Radar profiler reflectivity data collected at Ellington Field were used to infer mixing heights for selected flight days with available data. This information was used to understand how the mixing heights relate to the air quality characteristics. Note that the estimated mixing heights are representative of the mixing heights at Ellington Field. Given the complex local weather patterns in the Houston–Galveston Bay area, these mixing heights are probably not representative of mixing heights throughout the area.

To estimate mixing heights from the radar profiler data, the returned signal strengths were used to estimate the refractive index structure parameter (C_n^2). C_n^2 indicates the fluctuations of the index of refraction; the fluctuations are primarily due to gradients in the water content of air. Gradients in water content are strongest near boundaries, such as at the top of the convective boundary layer. Both theoretical and empirical studies have shown that C_n^2 peaks at the inversion located at the top of the CBL due to warm, dry aloft air entraining into cooler, moister air below the inversion (Dye et al., 1995; White, 1993; and Wyngaard and LeMone, 1980). A time-series plot of C_n^2 data and inferred mixing heights for August 18, 2000, is shown in **Figure 4-5**. In the figure, the red and white blocks indicate large C_n^2 and the likely maximum height of air mixing from the surface (shown as a black line). Note that at about 1700 UTC (1100 CST), the mixing height was estimated to be about 1250 m msl, whereas at about 1900 UTC (1300 CST), the mixing height was estimated to be about 1900 m msl.

4.8 CORRELATIONS

The principal goal of the correlation analysis performed was to understand the co-variation of ozone with NO_y, indicative of the precursor NO_x, and with the primary pollutants SO_2 and CO, which can lend insight into the sources of the observed NO_x. Scatter plots of O_3 vs. NO_y, O_3 vs. CO, and O_3 vs. SO_2 are presented for selected flights. Plots for all of the flights analyzed are presented in Appendix A. Scatter plots of SO_2 vs. NO_y are also presented; these plots contain lines representative of expected emission ratios from a variety of point and mobile sources, which allows a qualitative analysis of the source types that have contributed NO_x to a particular air mass. The slope observed between ozone and NO_y was used as a qualitative measure of the ozone production efficiency per unit of emitted NO_x for those flights where photochemical production of ozone was evidenced by a correlation between ozone and NO_y. That value, along with a qualitative indicator of whether the observations exhibited characteristics of photochemical activity, fresh emissions, or both, was determined

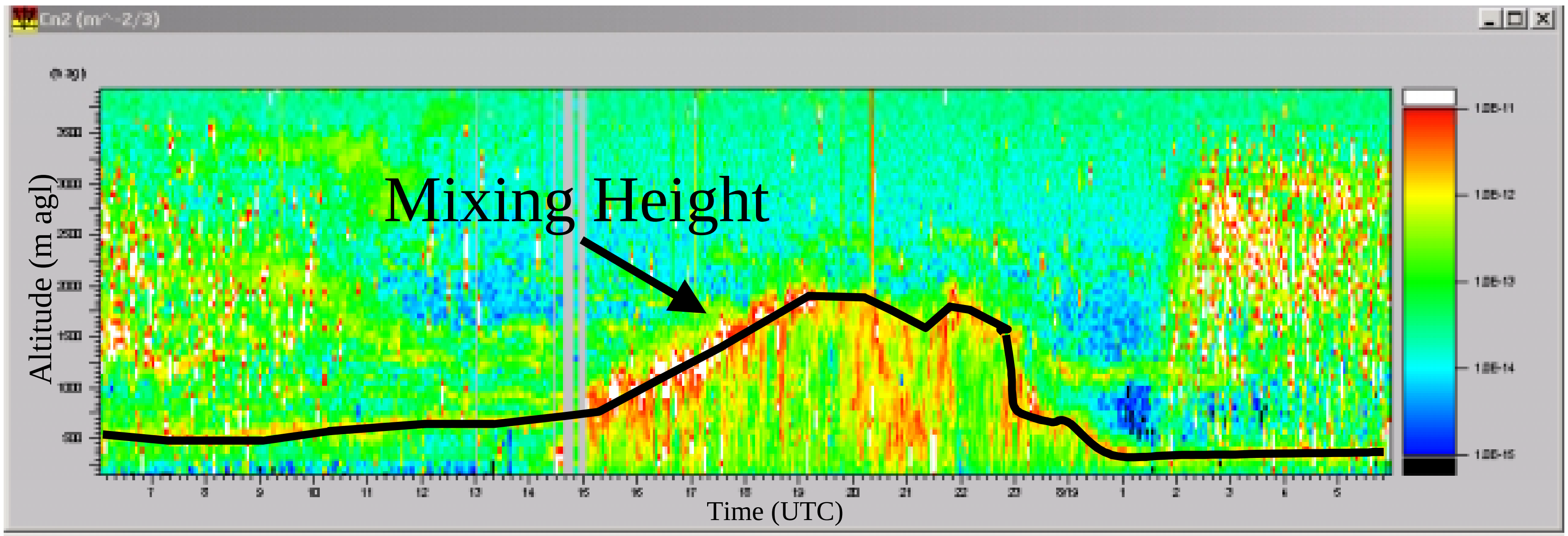


Figure 4-5. Radar wind profiler reflectivity data (C_n^2) and estimated mixing height for August 18, 2000, at Ellington Field, Houston.

4.9 POLLUTION ROSE PLOTS

Pollution rose plots were create using the Ellington Field radar profiler wind data and ozone data collected during the 1000- to 2000-ft msl morning box climbs over La Porte, Baytown, Trinity, Kemah; the 10,000-ft box climb just east of Texas City; and the afternoon 5000-ft box climb over Galveston Bay. For each morning box climb, the ozone data and wind data collected from 1000 to 2000 ft msl were averaged and rose plots were produced. An additional rose plot was produced using the morning data from 2000 to 5000 ft msl over Galveston Bay. For afternoon box climbs over Galveston Bay, the ozone data and wind data collected from 1000 to 5000 ft msl were averaged and pollution rose plots were produced.

A comparison of the aircraft wind data to the profiler wind data showed that the aircraft wind data are not consistent with the radar profiler wind data and the aircraft data appear invalid at times, as discussed in Section 6. Therefore, the radar profiler data were used in the pollution rose plots.

5. CASE STUDIES

The main purpose of this project was to characterize the air quality data collected during Baylor University's year 2000 flights and, in doing so, address some technical questions regarding air pollution in the Houston–Galveston area (see Section 1 for details). For 20 selected flights (shown in Table 3-1 of Section 3), we reviewed the aloft ozone, NO_y, NO, SO_2, and temperature data collected by the Baylor aircraft, in conjunction with CAMS air quality and meteorological data, visible satellite data, radar profiler wind and reflectivity data, weather charts, and Eta Data Assimilation System (EDAS) data. Section 4 presented example plots that were used in this review and discussed how the plots were interpreted. This section presents the characterization of this data and is organized chronologically. A summary of the results and conclusions derived in part from this characterization is contained in Section 2.

5.1 FLIGHT 135, AUGUST 18, 2000

On August 18, 2000, there was one afternoon flight confined to east, southeast and central Houston with a single box climb over Galveston Bay to 5000 ft msl (1524 m msl) and several traverses over eastern Houston near the Houston Ship Channel (**Figure 5-1**). The typical flight altitude was approximately 1500 ft msl (457 m msl).

5.1.1 Overview of Meteorology and Air Quality

The synoptic pattern over Houston as depicted by the 0600 CST August 18, 2000 analysis (**Figure 5-2**) included a broad ridge of high pressure at 500 mb over the southern third of the United States with a small anticyclone centered over Texas. The anticyclonic circulation was also observed on August 19, 2000.

The mixing height as estimated by profiler reflective data (C_n^2) at Ellington Field was about 1640 ft msl (500 m msl) overnight and during the early morning (**Figure 5-3**). Beginning just after 0900 CST (1500 UTC), the mixing height rose steadily to approximately 6560 ft msl (2000 m msl) by 1300 CST (1900 UTC). At 1429 CST, the temperature sounding collecting during the Galveston Bay box climb shows that the mixing height was about 4600 ft msl (1400 m msl) (**Figure 5-4**).

Within the first 1000 m msl, the winds were onshore for the entire day, reinforced by southerly winds at about 1000 to 1400 m msl (**Figure 5-5**). Near the surface, the winds were light southwesterly in the morning, turning to a light southeasterly Bay Breeze around 1430 CST, and shifting to a moderate southerly Gulf Breeze by 1600 CST. This wind pattern was very similar on the following day. Both the radar profiler and EDAS back-trajectories show transport from the Gulf of Mexico at all back-trajectory levels (140 m msl, 700 m msl, and 1500 m msl) with no evidence of recirculation or stagnation. With no recirculation or stagnation, ozone concentrations were not as high as compared to other flight days with lighter winds and/or recirculation.

5.1.2 Characteristics of Ozone and NO_x

Horizontal

- No morning flight was performed so general morning characteristics could not be assessed.
- The peak afternoon ozone concentration observed by the aircraft was approximately 115 ppb, observed at 1700 ft msl (520 m msl) during the Galveston Bay box climb at 1429 CST (Figure 5-4). This peak was above the maximum height of the Bay Breeze of about 1640 ft msl (500 m msl) (Figure 5-5). Within the Bay Breeze between Ellington Field and Galveston Bay from 250 to 1400 ft msl (76 to 427 m msl), ozone concentrations were about 70 to 80 ppb.
- The peak surface ozone concentration was 130 ppb north of Houston at Conroe at 1730 CST. Sites south of Houston had ozone peak concentrations of about 70 to 80 ppb, which is consistent with the onshore southerly flow.
- Aloft ozone concentrations were generally similar to the surface ozone concentrations. For example, on the east side of Houston, aloft concentrations at 1500 CST at the traverse altitude of approximately 1500 ft msl (457 m msl) were generally 80 to 90 ppb while the ozone concentrations at nearby CAMS 607 were approximately 75 ppb at 1500 CST (**Figure 5-6**).
- The aloft ozone observed in the area near CAMS 607 is associated with SO_2 concentrations of up to 10 ppb and NO_y concentrations of up to 30 ppb between 1455 and 1505 CST (**Figure 5-6)**.
- Since the winds in this layer were from the south and southeast, it is possible that this layer of ozone, NO_y, and SO_2 is related to emissions to the south and southeast in the Ship Channel area.

Vertical

- The vertical profile obtained during takeoff, from 250 to 1500 ft msl (76 to 457 m msl) (**Figure 5-7**), and the only box climb during this afternoon flight, from 1500 to 5000 ft msl (457 to 1524 m msl), showed that ozone, NO, and NO_y concentrations over Galveston Bay varied considerably with elevation (Figure 5-4).
  - From 250 ft msl (76 m msl) (the start of the ascent after takeoff) to 1100 ft msl (335 m msl), ozone concentrations were approximately 70 to 80 ppb while NO_y concentrations were approximately 7 ppb.
  - At 1200 ft msl (365 m msl), there was a slight decrease in ozone and an increase in NO_y while NO increased from 0 to 2 ppb at this level. This layer of titrated ozone at 1250 ft msl (381 m msl) did not contain SO_2. The decreasing ozone associated with this layer suggests that the layer was relatively fresh.
  - At 1500 to 2000 ft msl (457 to 610 m msl), there was a layer of SO_2 (15 ppb) and NO_y (5 to 10 ppb) but no NO. At this altitude, ozone concentrations peaked at 115 ppb. This suggests that this layer was old enough to allow for the ozone production and not titration, as with the 1200 ft msl (365 m msl) layer.

- At 2800 to 3400 ft msl (853 to 1036 m msl), there was another layer; however, this layer did not contain SO_2, but had peak NO concentrations of 12 ppb and peak NO_y concentrations of 40 ppb. The NO had titrated ozone and ozone concentrations dropped to 45 ppb at 3000 ft msl, again suggesting that the layer was fresh. Between 3400 and 4000 ft msl (1036 and 1219 m msl), there were two more layers with NO_y and titrated ozone and little NO and SO_2.
- From 4000 to 4700 ft msl (1220 to 1430 m msl), ozone concentrations increased to about 85 ppb. From 4700 ft msl to 5000 ft msl (1430 m msl to 1524 m msl), there was a temperature inversion, where ozone concentrations were about 70 ppb. The aircraft did not fly higher than 5000 ft msl (1524 m msl).

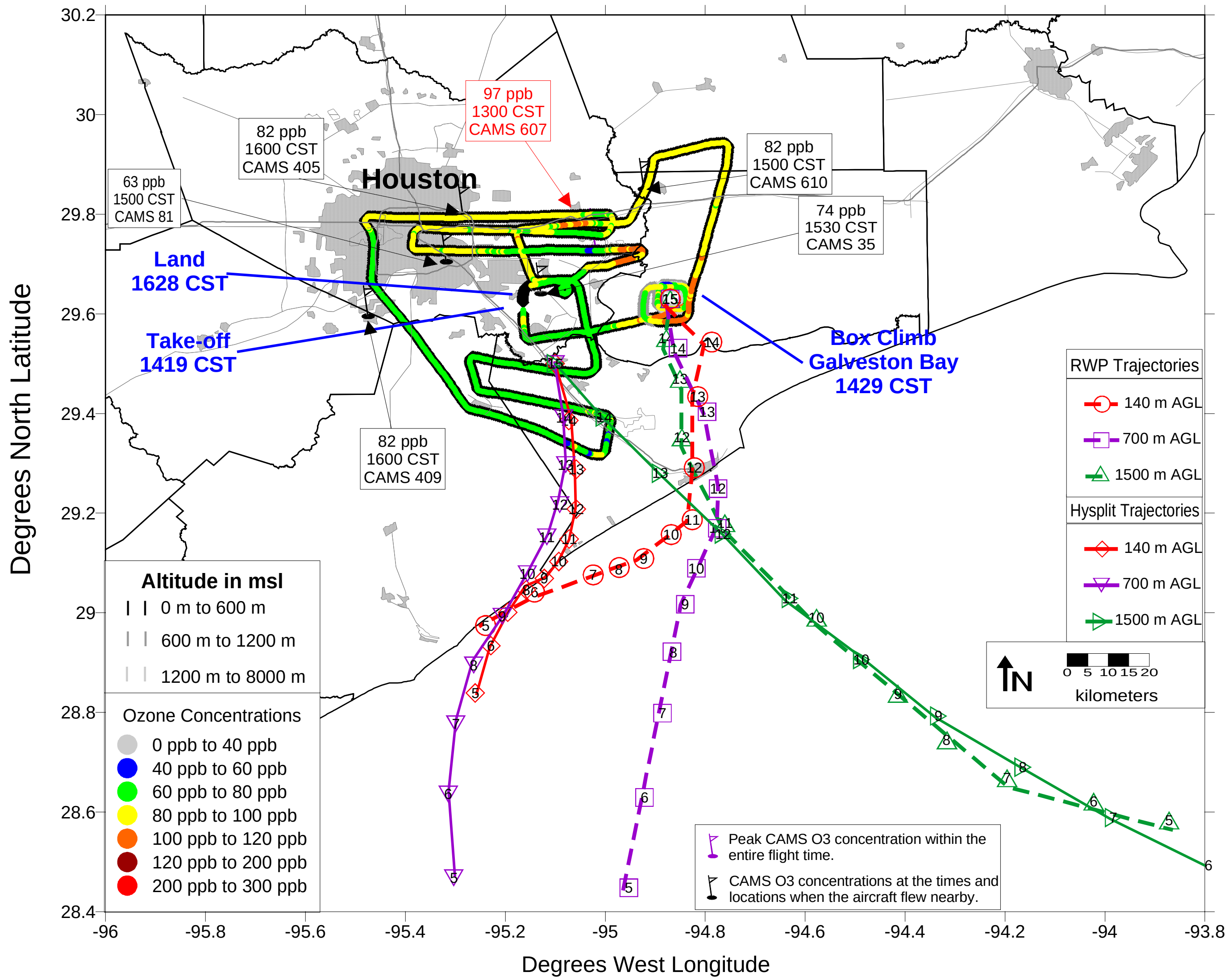


Figure 5-1. Flight 135 flight position, altitude, aloft ozone concentrations, CAMS surface ozone concentrations, and back-trajectories on the afternoon of August 18, 2000.

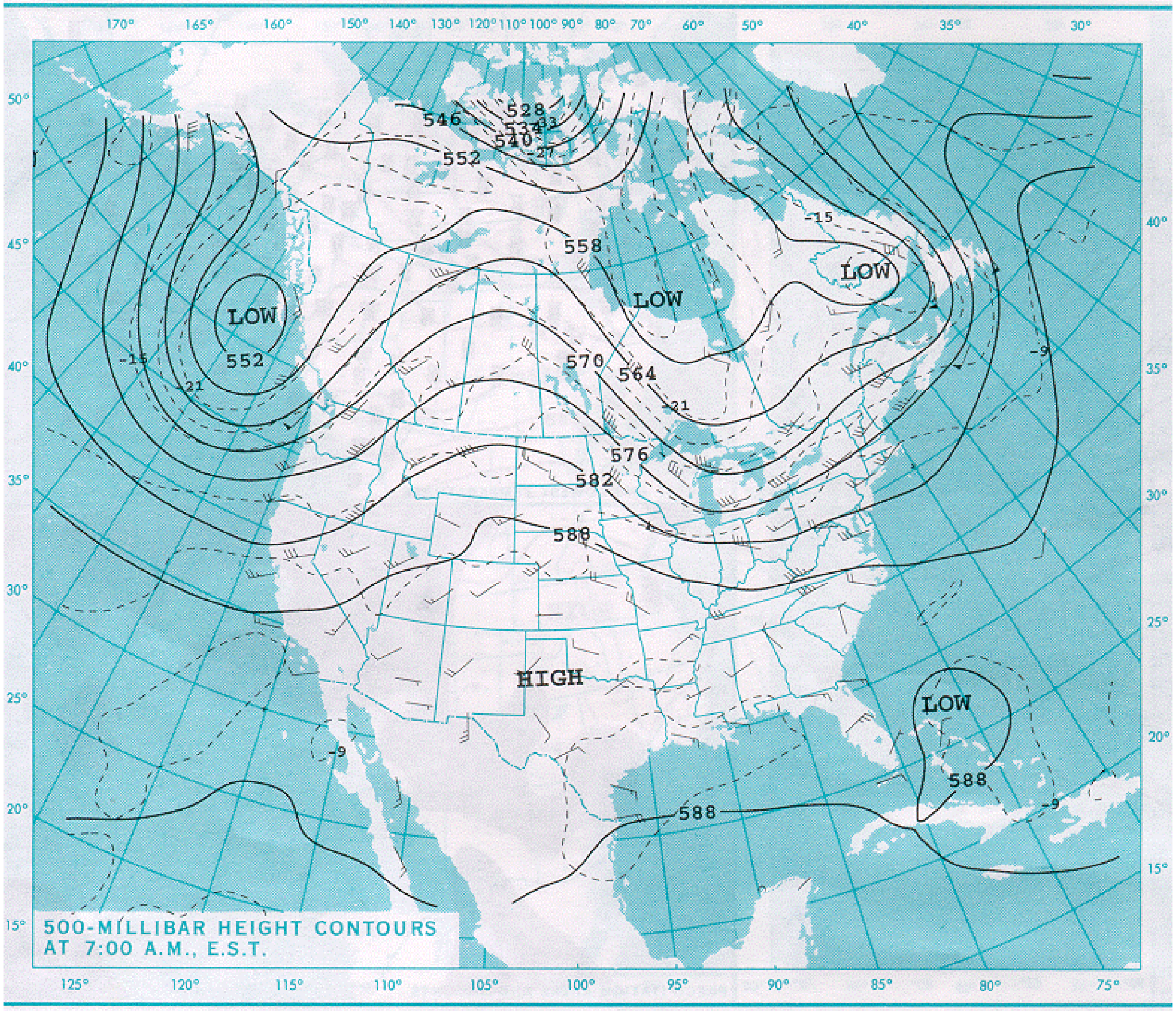


Figure 5-2. Height contours of the 500-mb pressure surface at 0600 CST on August 18, 2000.

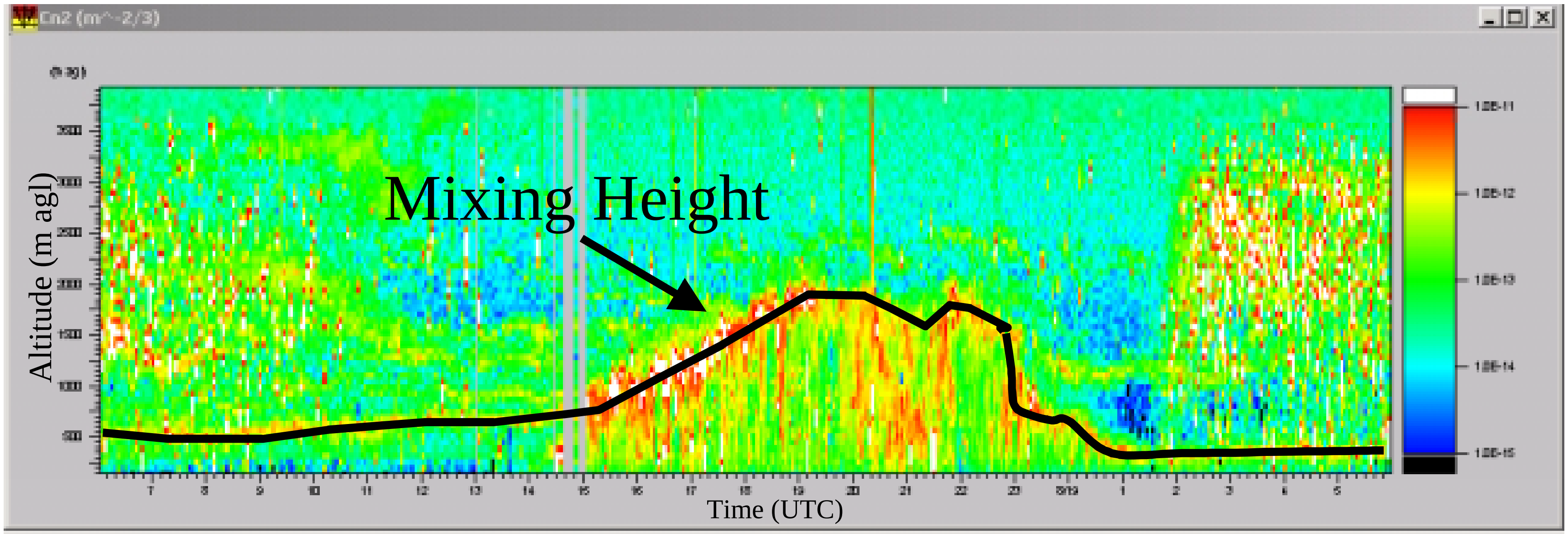


Figure 5-3. Radar wind profiler reflectivity data (C_n^2) and estimated mixing height for August 18, 2000, at Ellington Field, Houston. The profiler is 10 m above msl.

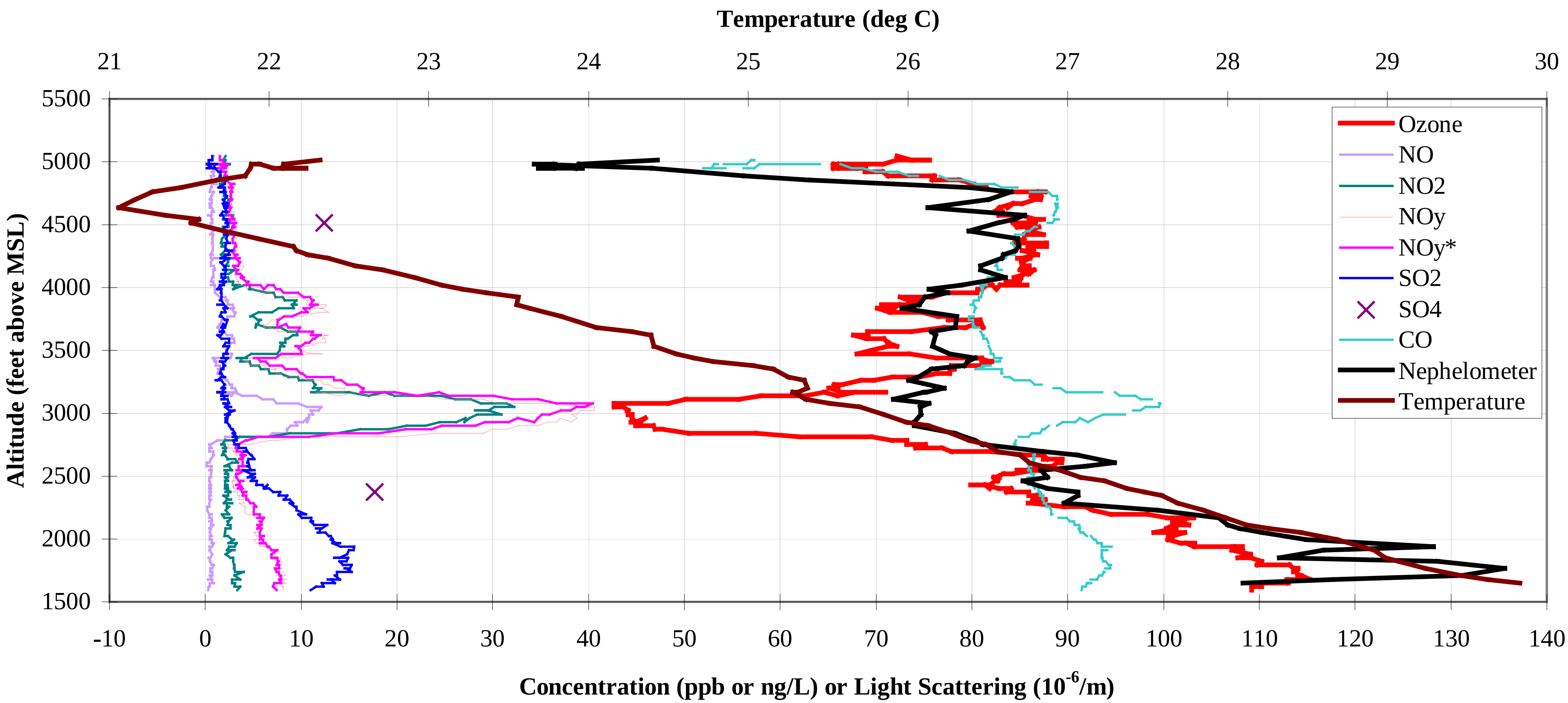


Figure 5-4. Vertical profile of air quality and temperature data collected over Galveston Bay from 1429 to 1436 CST on August 18, 2000.

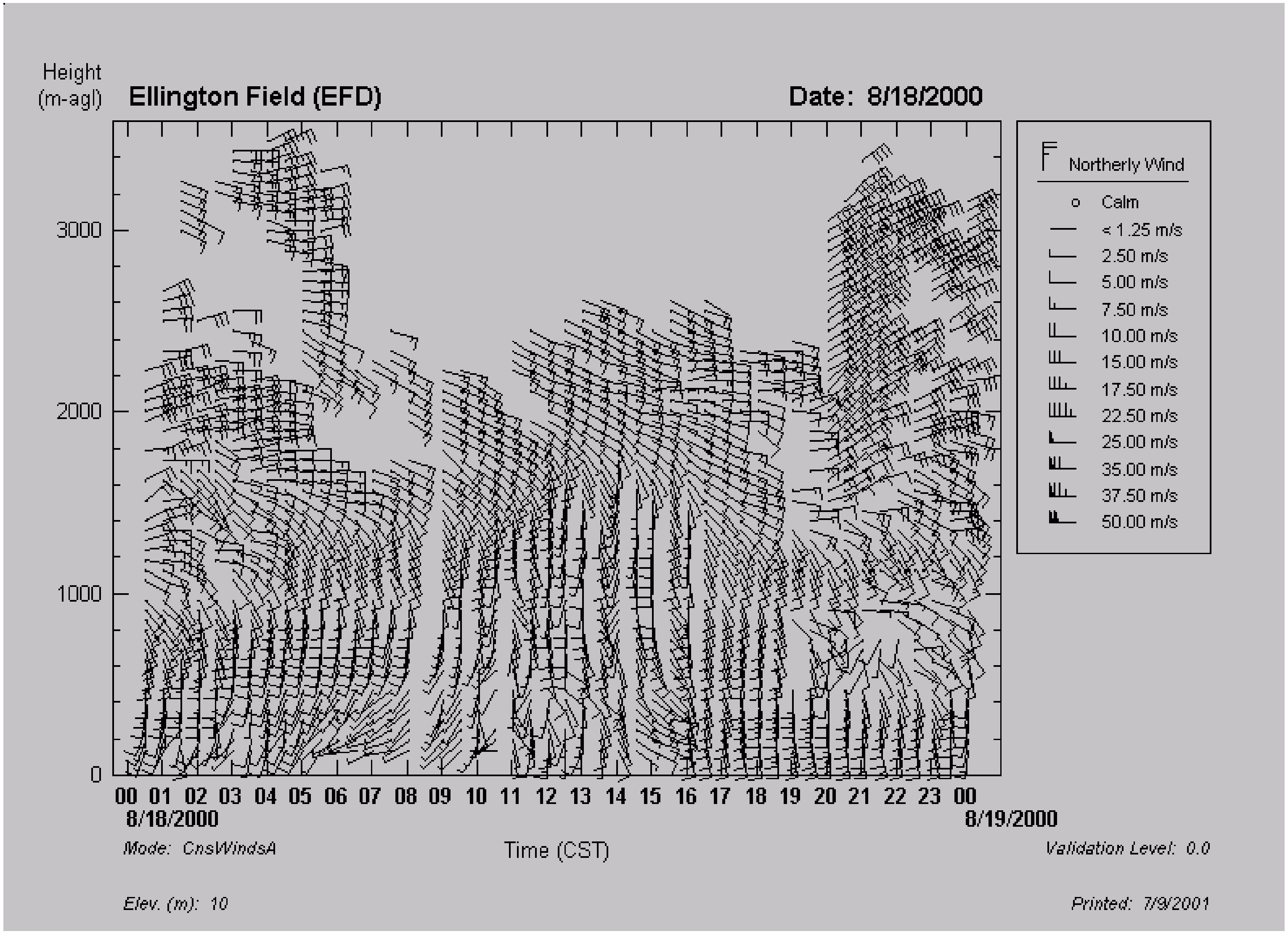


Figure 5-5. Radar wind profiler data for August 18, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

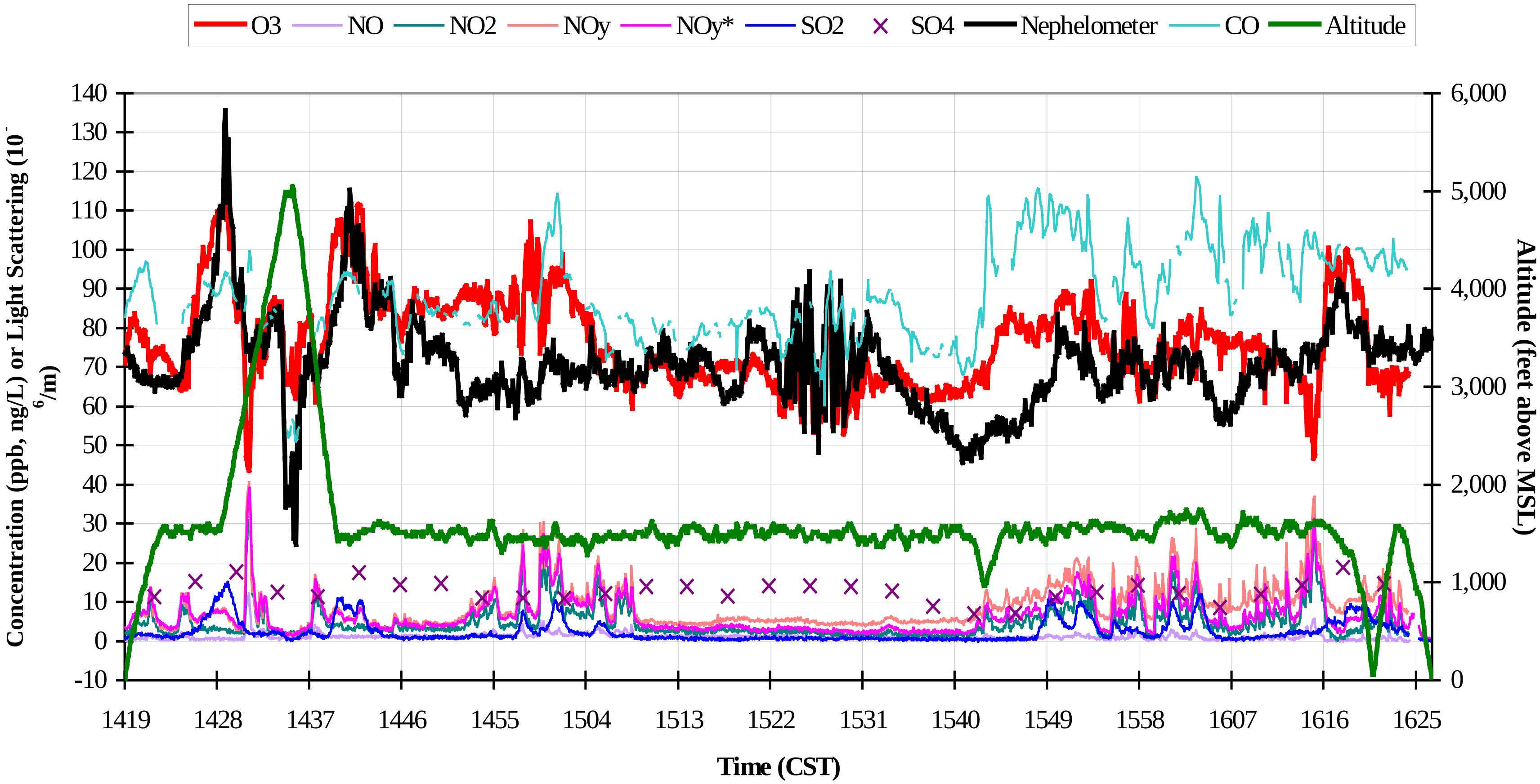


Figure 5-6. Time-series plot of air quality and temperature data collected from 1419 to 1628 CST on August 18, 2000.

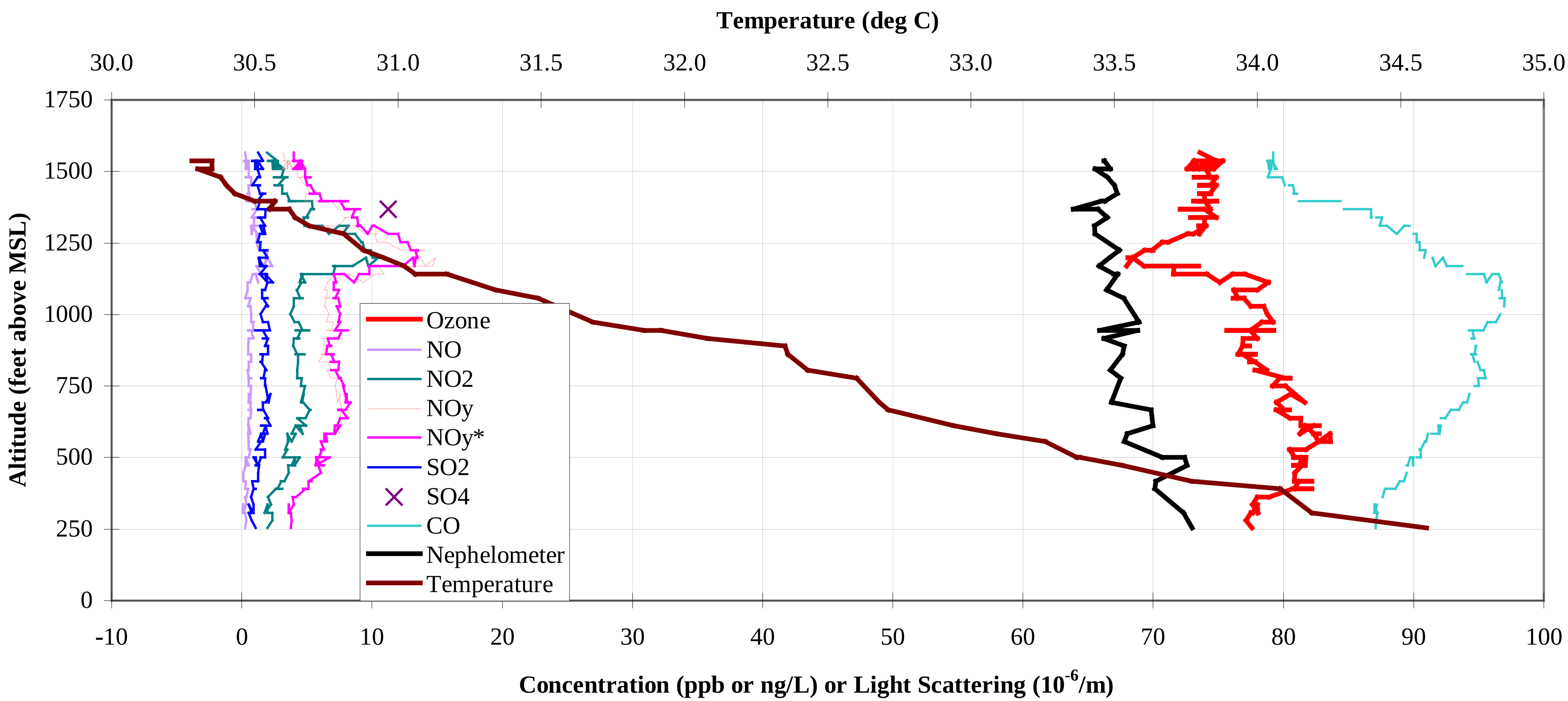


Figure 5-7. Vertical profile of air quality and temperature data collected upon takeoff from Ellington Field from 1420 to 1424 CST on August 18, 2000.

5.2 FLIGHT 136A AND 136B, AUGUST 19, 2000

On August 19, 2000, there was a morning and an afternoon flight. The morning flight consisted of a series of box climbs up to approximately 2000 ft msl (610 m msl) along with one box climb to 10,000 ft msl (3048 m msl) east of Texas City (**Figure 5-8**). When box climbs were not being flown, the flight altitude was maintained at approximately 1000 ft msl (305 m msl). The afternoon flight was confined to southeast and central Houston with a single box climb over Galveston Bay and several traverses over eastern Houston near the Ship Channel (**Figure 5-9**). When box climbs and traverses were not being flown, the typical flight altitude was about 1500 ft msl (457 m msl).

5.2.1 Overview of Meteorology and Air Quality

The synoptic pattern over Houston as depicted by the analysis of 0600 CST, August 19, 2000 (**Figure 5-10**), included a broad ridge of high pressure at 500 mb over the southern third of the United States with a small anticyclone centered over Texas.

The mixing heights as estimated by profiler reflectivity data (C_n^2) were about 1312 to 1640 ft msl (400 to 500 m msl) overnight and during the early morning, gradually increasing beginning at 0900 CST (1500 UTC) before peaking at 5900 ft msl (1800 m msl) by 1300 CST (1900 UTC) (**Figure 5-11**). However, mixing heights do vary throughout the region due to the Bay and Gulf Breezes. For example, while mixing heights were about 4920 ft msl (1500 m msl) at Ellington Field at 1200 CST (1800 UTC), the air quality data indicate there was a shallow layer of fresh emissions contained below approximately 1970 ft msl (600 m msl) over Galveston Bay at this time (**Figure 5-12**).

Wind patterns were similar to those observed on the previous day. Within the lowest 1000 m msl, the winds were onshore overnight and most of the day with light southwesterly winds in the morning, a light southeasterly Gulf Breeze at 1200 CST, followed by a moderate Gulf Breeze at 1600 CST (**Figure 5-13**). The Gulf Breeze front is seen in the visible satellite image at 1209 CST (1809 UTC) over Ellington Field (**Figure 5-14**).

As shown in Figure 5-9, both the radar profiler and EDAS 140-m agl and 700-m msl back-trajectories show short transport distances from 0500 to 1100 CST (the time of peak surface ozone concentrations) with stagnation in the late morning hours. At 140 m agl, the back-trajectories' paths were from the west. At 700 m agl, the back-trajectories were from the southwest. At 1500 m agl, the back-trajectories were from the south/southeast with much longer transport distances.

The air quality observations were, in general, consistent with the observed meteorology. Peak ozone concentrations of 146 ppb were observed in the Baytown vicinity at 1100 CST at CAMS 610. By afternoon, the peak ozone concentrations shifted to north and west of Houston, presumably associated with the onset of the afternoon Gulf Breeze. The highest ozone concentration in the afternoon was 121 ppb at CAMS 08. Once the onset of the Gulf Breeze was observed at a site, ozone concentrations generally decreased 30 to 50 ppb within an hour or two.

5.2.2 Characteristics of Ozone and NO_x

Morning Horizontal

- Aloft ozone concentrations, as observed during morning traverses and the box climb above the morning boundary layer were 40 to 60 ppb. For example, in the La Porte box climb (**Figure 5-15**), ozone concentrations of 60 to 70 ppb were observed above 1300 ft msl (400 m msl). The air at this level came off the Gulf of Mexico as indicated by the 24-hr EDAS back-trajectories (**Figure 5-16**).
- During the early morning hours, surface ozone concentrations were titrated at most CAMS sites (especially in the central Houston area) where ozone concentrations ranged from 0 to 30 ppb. NO_x concentrations were typically around 30 ppb during the early morning hours. For example, at 0600 CST, ozone concentrations were 0 ppb at CAMS 35 near Spencer and NO_x concentrations were 30 ppb.

Morning Vertical

Two inversions were observed during the morning box climbs:

- One inversion was located at 300 ft msl (91 m msl) as observed during the Trinity Bay box climb (**Figure 5-17**). Below this inversion, ozone concentrations were around 30 ppb, NO_y concentrations were around 17 ppb, and NO concentrations were near 0 to 1 ppb.
- The second inversion was at 1000 ft msl (305 m msl) (Figure 5-17). Between these inversions, ozone concentrations were around 55 ppb. In this layer, NO_y concentrations were approximately 3 ppb, and SO_2 and NO concentrations were near 0 ppb. Besides a few specific pollution spikes, similar profiles of air quality were observed during the other morning box climbs.

Afternoon Horizontal

- Surface ozone concentrations peaked during the afternoon, with the highest ozone concentrations found just north of the Ship Channel. One exception was found at CAMS 610 located north of Baytown, where a peak ozone concentration of 146 ppb was observed at 1100 CST before the onset of the Bay Breeze at 1200 CST, as observed by the radar wind profiler at Ellington Field (Figure 5-13). A few sites close to Galveston Bay peaked during the early afternoon (CAMS 607 in Baytown peaked at 95 ppb at 1200 CST and CAMS 18 near Spencer peaked at 95 ppb at 1300 CST).
- Ozone concentrations aloft within the region north of the Ship Channel were observed from 80 ppb over Trinity Bay at 1300 CST to as high as 136 ppb over Baytown at 1235 CST at an elevation of 1500 ft msl (**Figure 5-18**). High concentrations of NO_y (as high as 20 ppb) and SO_2 and NO concentrations of 10 ppb and 0 ppb, respectively, were observed within this area. Given that the trajectories show transport from south of central Houston, and from the Ship Channel, those high concentrations were probably associated with emissions from both areas.
- The Bay Breeze began around 1200 CST, followed by a stronger, more southerly breeze at 1400 CST as observed in the radar wind profiler data (Figure 5-13).

- Ozone concentrations began to drop as the Gulf Breeze started to fill in between 1200 and 1600 CST. For example, CAMS 35 near Ellington Field had a peak ozone concentration of 95 ppb at 1300 CST. The ozone concentration then dropped to 90 ppb the next hour and was down to 75 ppb by 1600 CST.

Afternoon Vertical

- The only box climb during the afternoon flight shows that ozone, NO, and NO_y concentrations over Galveston Bay vary considerably with elevation with several distinct layers (Figure 5-12). The box climb was flown from 1210 to 1220 CST.
  - From 1500 ft msl (457 m msl), the start of the box climb, to 1900 ft msl (600 m msl), ozone concentrations were approximately 50 ppb while NO_y and NO concentrations were approximately 27 and 7 ppb, respectively. Although no temperature inversion is observed at 1900 ft msl (600 m msl), the profiler wind data (Figure 5-13) shows a wind transition at this altitude and time (1200 CST); therefore, this layer of titrated ozone may be related to air in the bay boundary layer.
  - From 1800 to 3200 ft msl (550 to 976 m msl), there was a layer of SO_2 (up to 10 ppb), NO_y (up to 5 ppb), and ozone (up to 115 ppb), but NO was 0 ppb. The 700-m back-trajectory (Figure 5-9) indicates that air at this altitude probably originated from an area over Texas City in the morning at 0800 or 0900 CST.
  - From 3200 to 4000 ft msl (977 to 1220 m msl), a calibration was completed; thus, this data on the plot should be ignored. Above 4000 ft msl (1220 m msl), ozone concentrations reached 60 ppb while NO_y, NO_x, and SO_2 concentrations were about 0.
- During the approach to landing at Ellington Field at 1407 CST, the aircraft monitored ozone concentrations of 85 ppb from 1200 ft msl (366 m msl) down to the surface (Figure 5-18) suggesting that the atmosphere below 1200 ft msl (366 m msl) had become well mixed by this time, which is consistent with the estimated mixing heights from the radar profiler data.

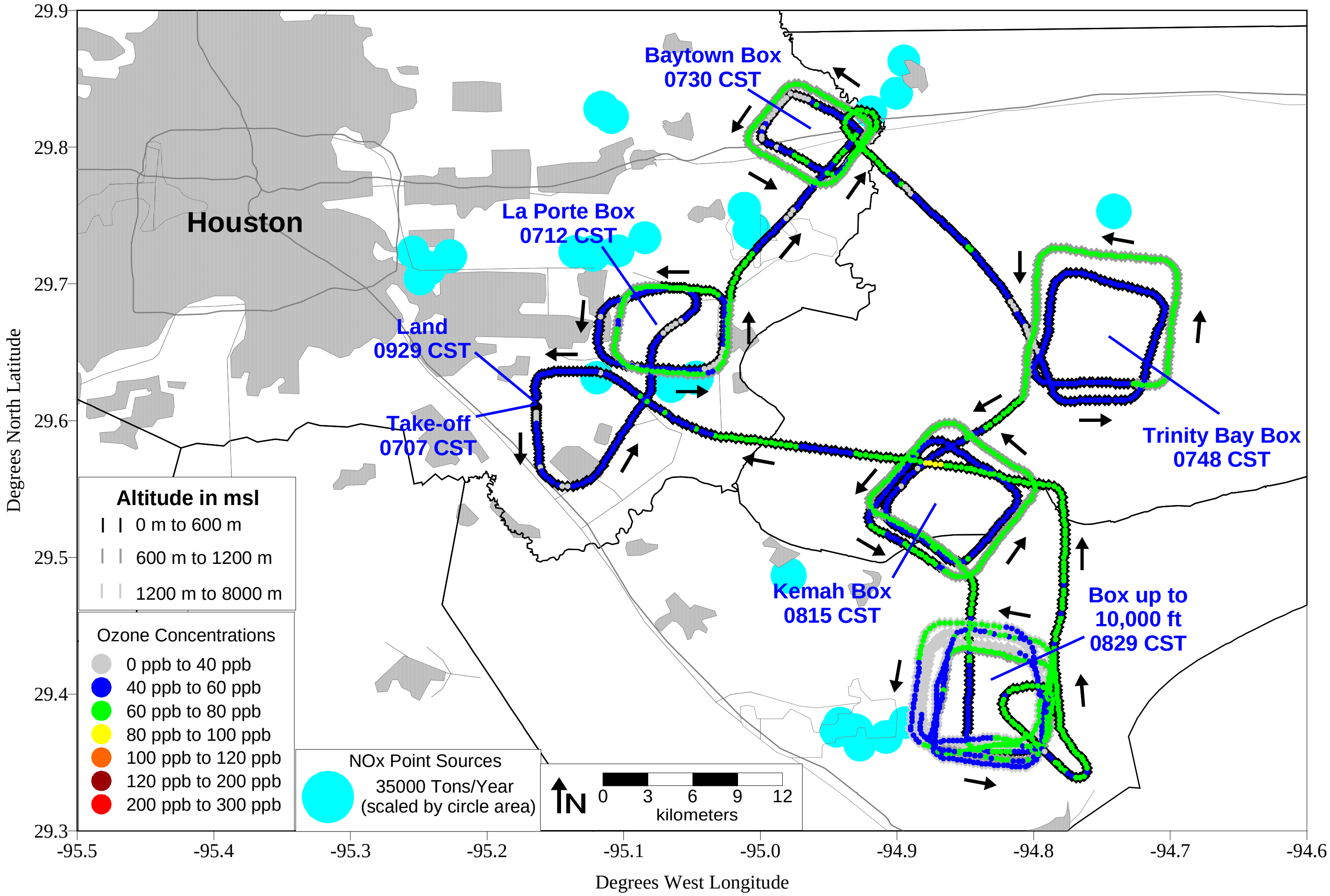


Figure 5-8. Flight 136 flight position, altitude, and aloft ozone concentrations on the morning of August 19, 2000.

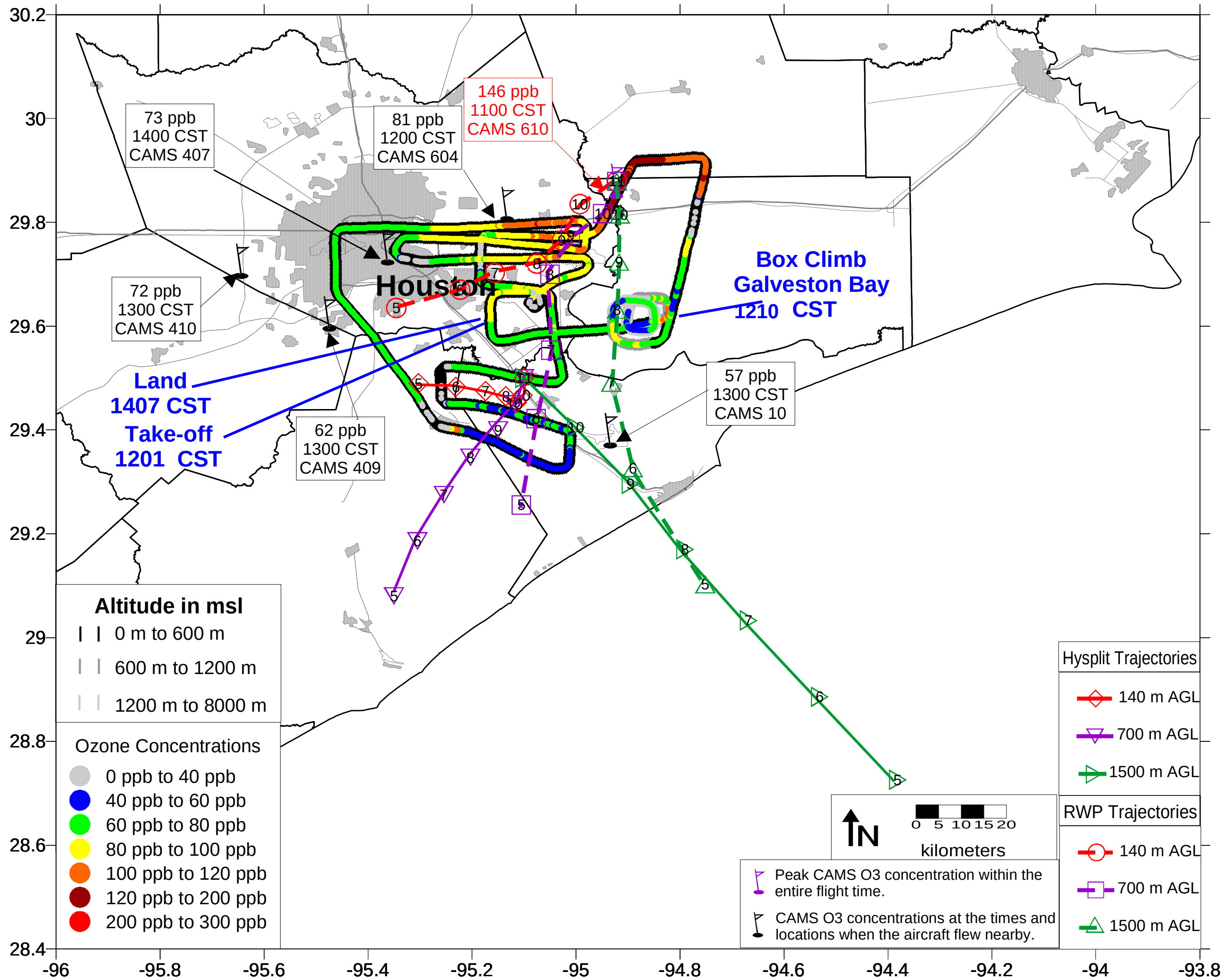


Figure 5-9. Flight 136 flight position, altitude, aloft ozone concentrations, CAMS surface ozone concentrations, and back-trajectories on the afternoon of August 19, 2000.

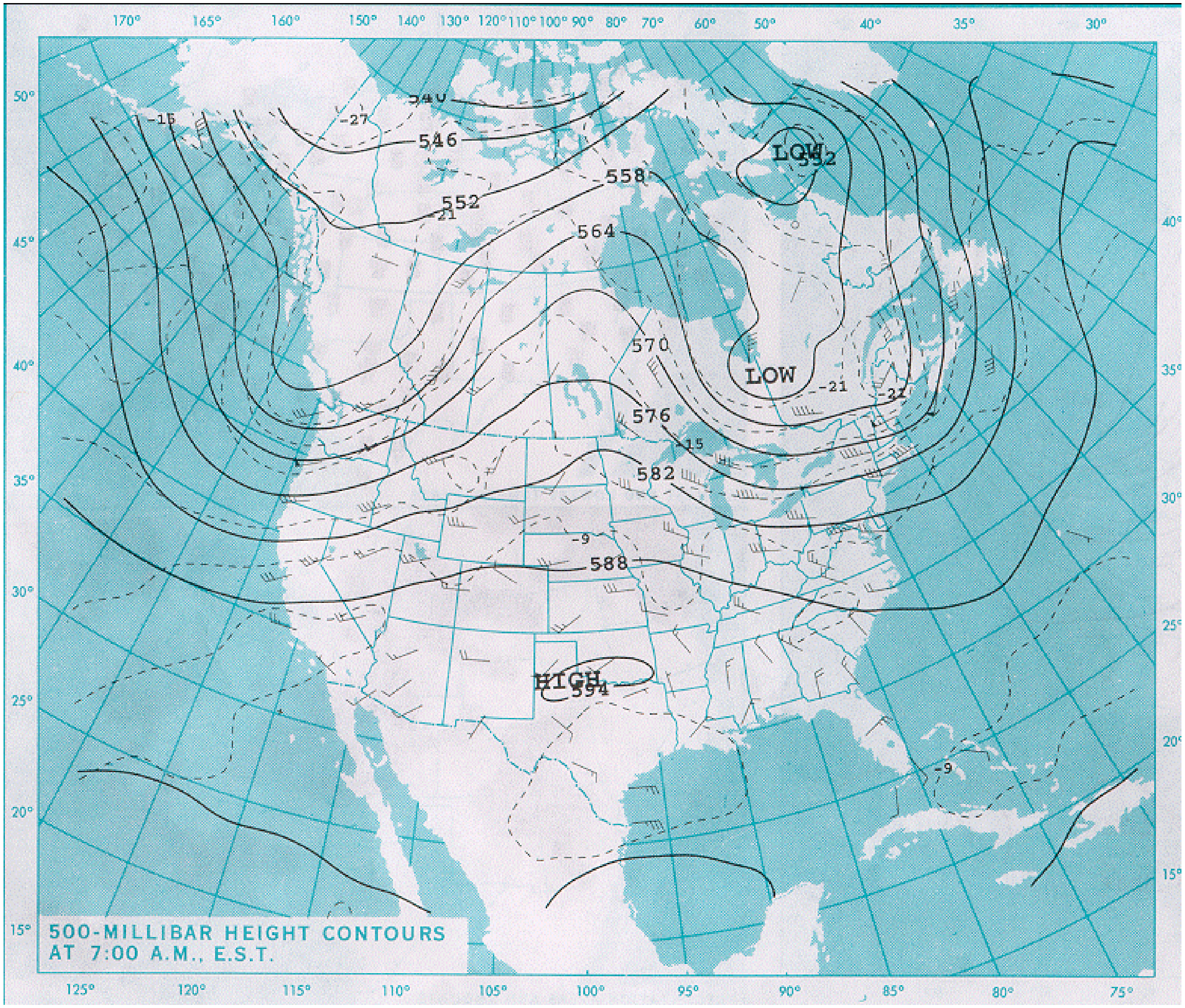


Figure 5-10. Height contours of the 500-mb pressure surface at 0600 CST on August 19, 2000.

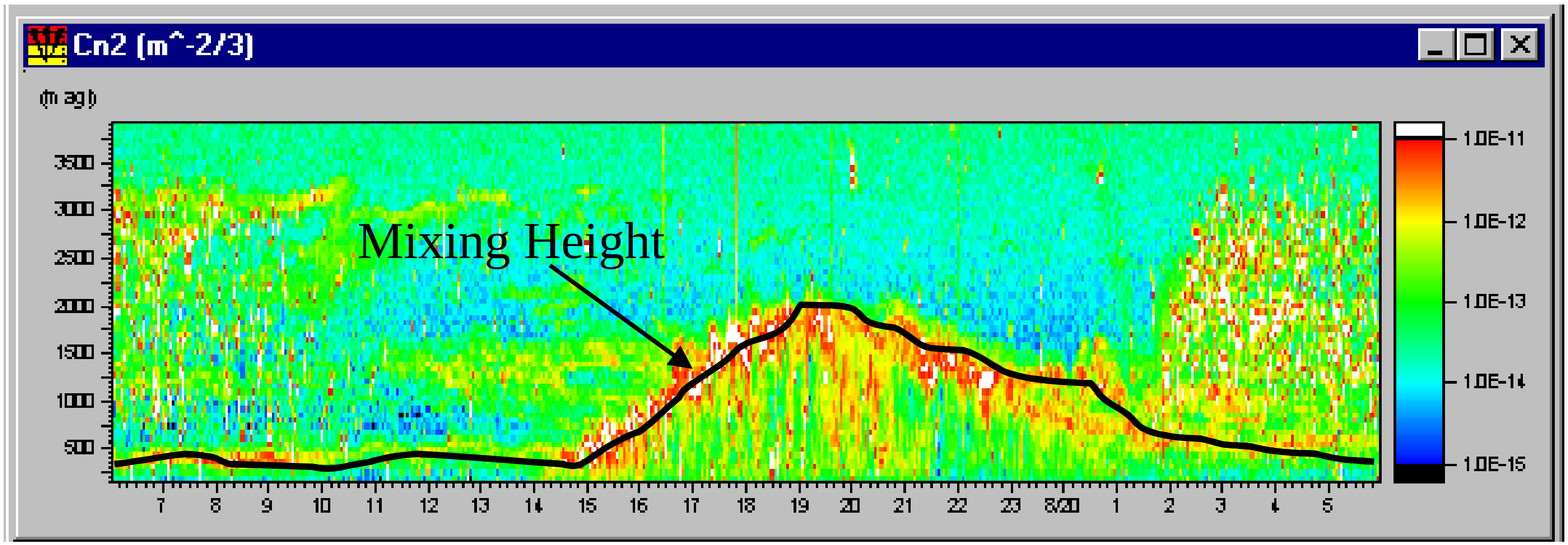


Figure 5-11. Radar wind profiler reflectivity data (C_n^2) and estimated mixing height for August 19, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

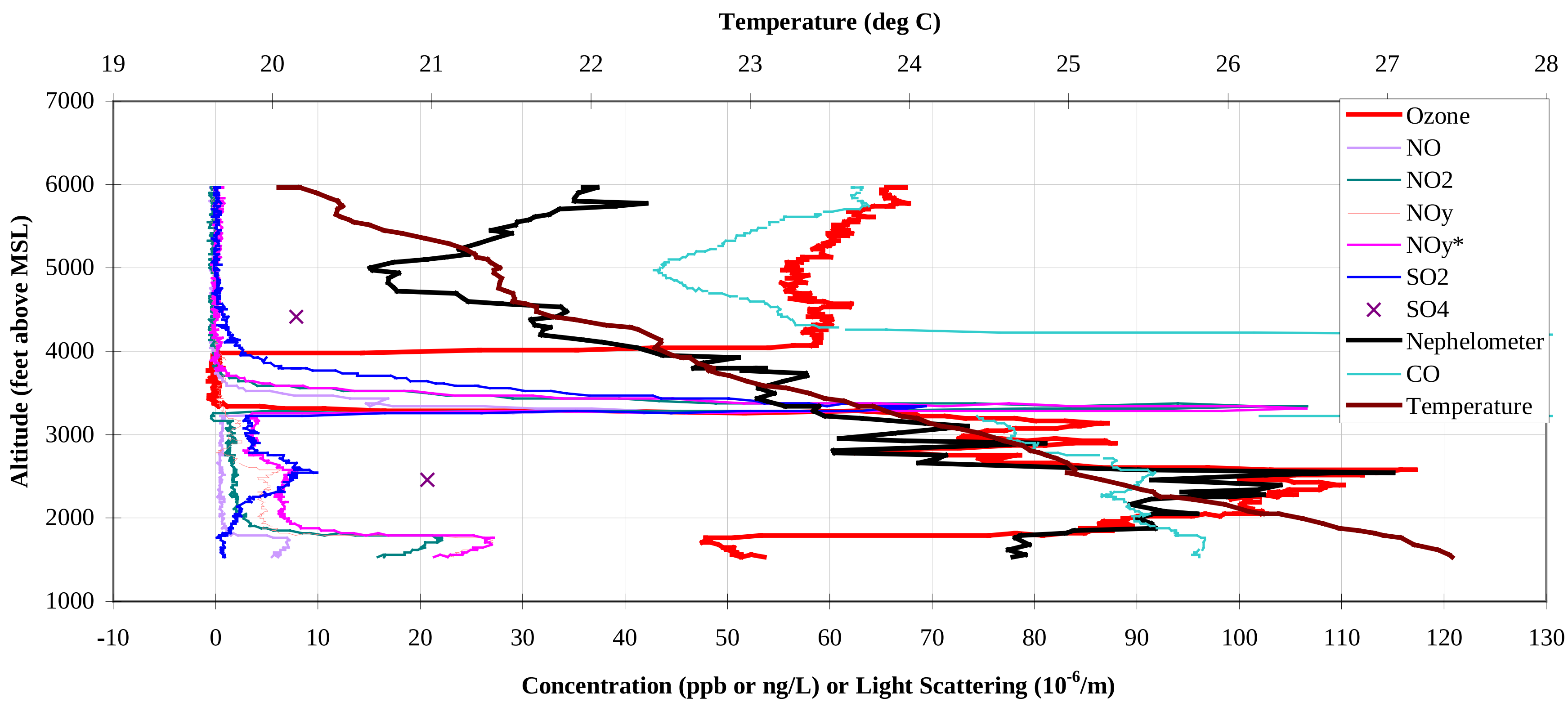


Figure 5-12. Vertical profile of air quality and temperature data collected over Galveston Bay from 1210 to 1220 CST on August 19, 2000.

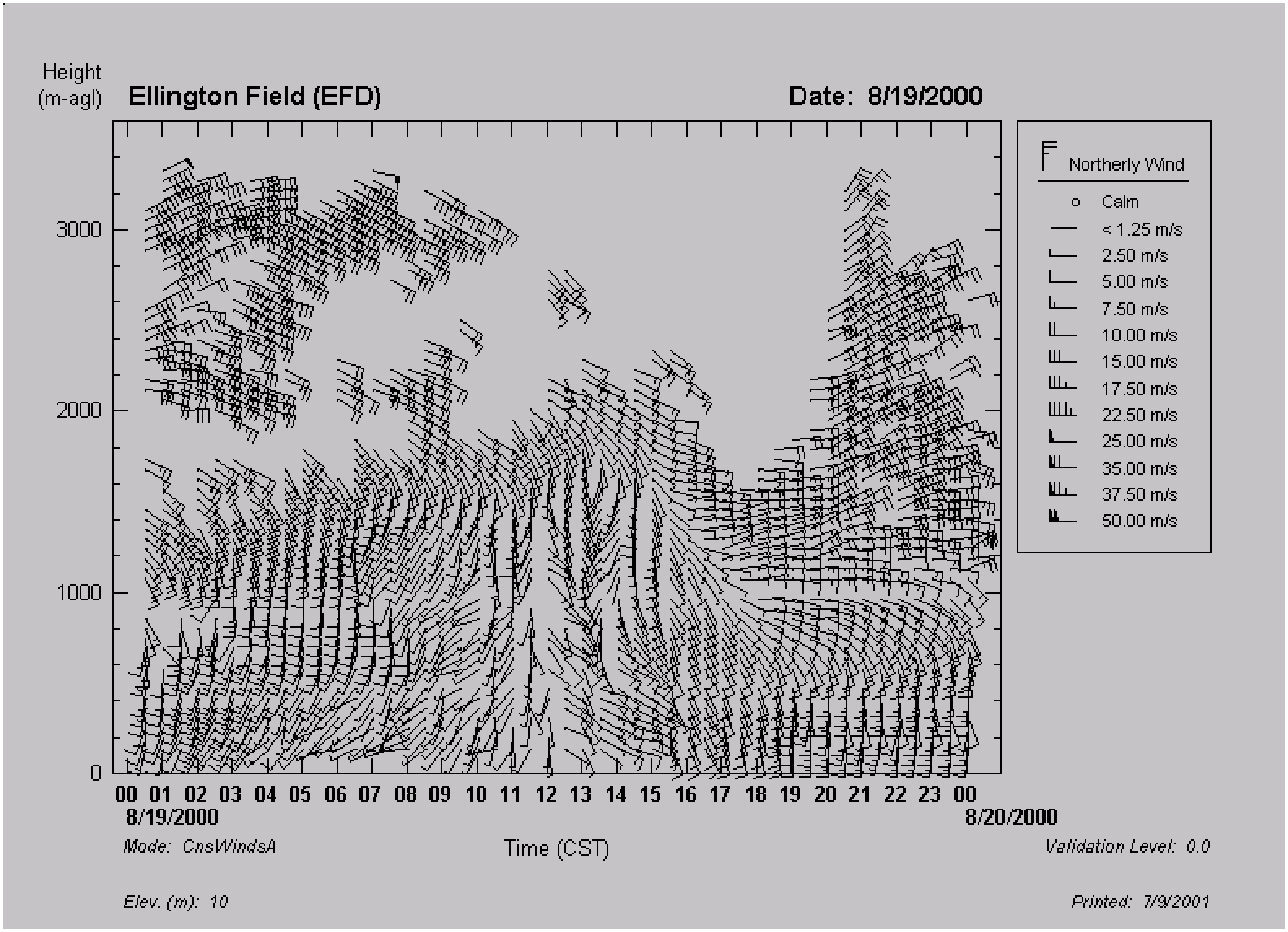


Figure 5-13. Radar wind profiler data for August 19, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

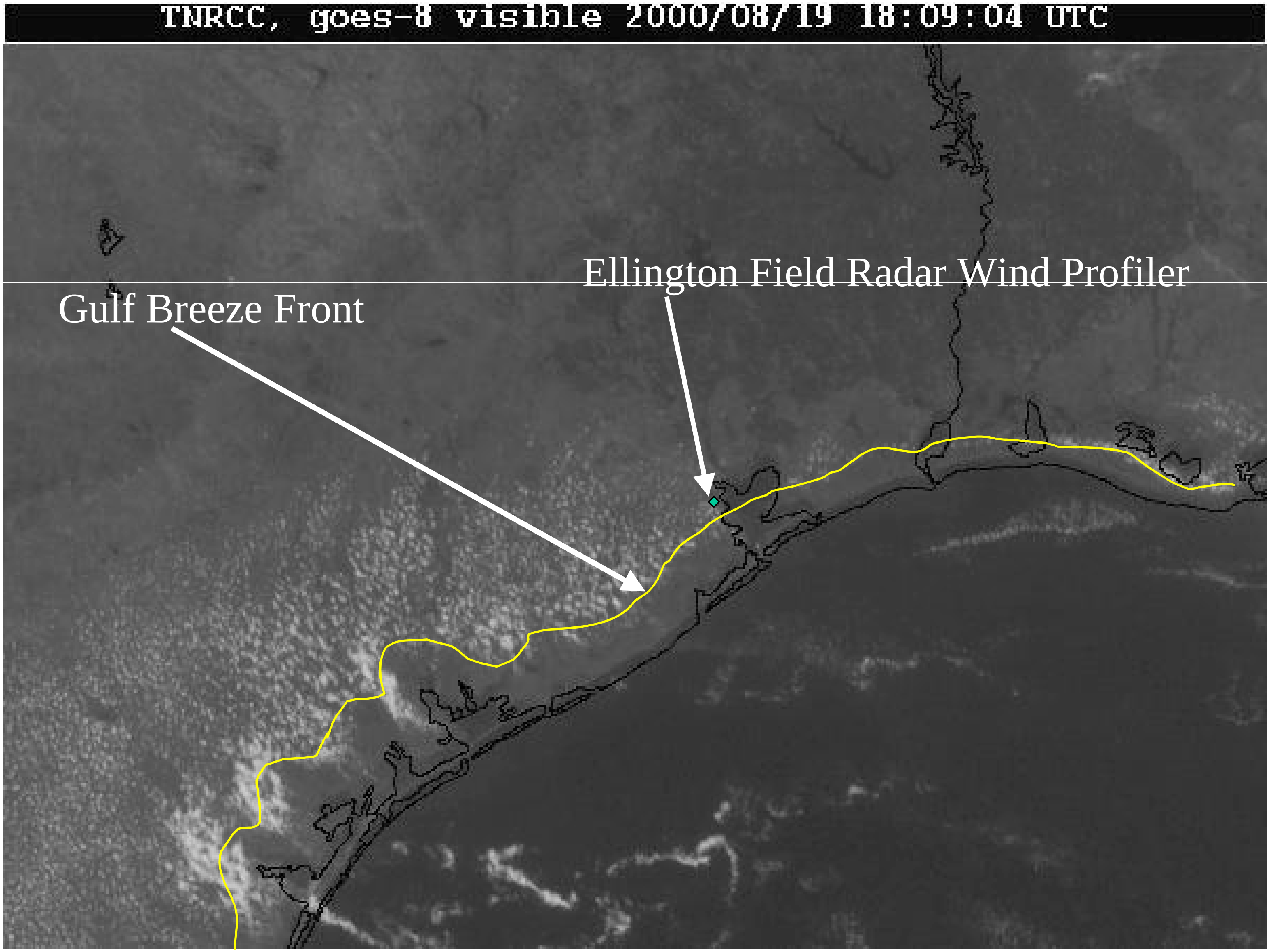


Figure 5-14. Visible satellite imagery at 1209 CST (1809 UTC) on August 19, 2000.

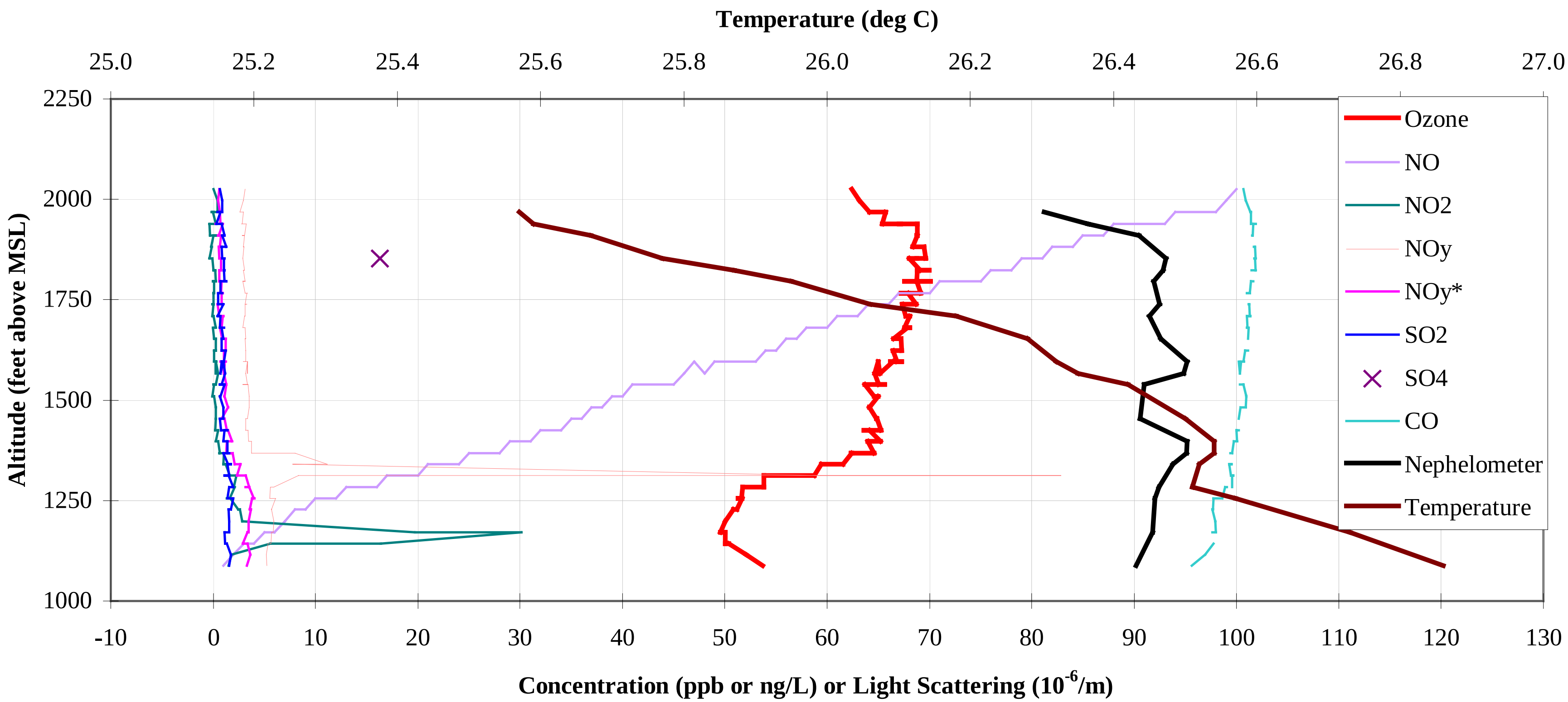


Figure 5-15. Vertical profile of air quality and temperature data collected over La Porte, Texas, from 0719 to 0722 CST on August 19, 2000.

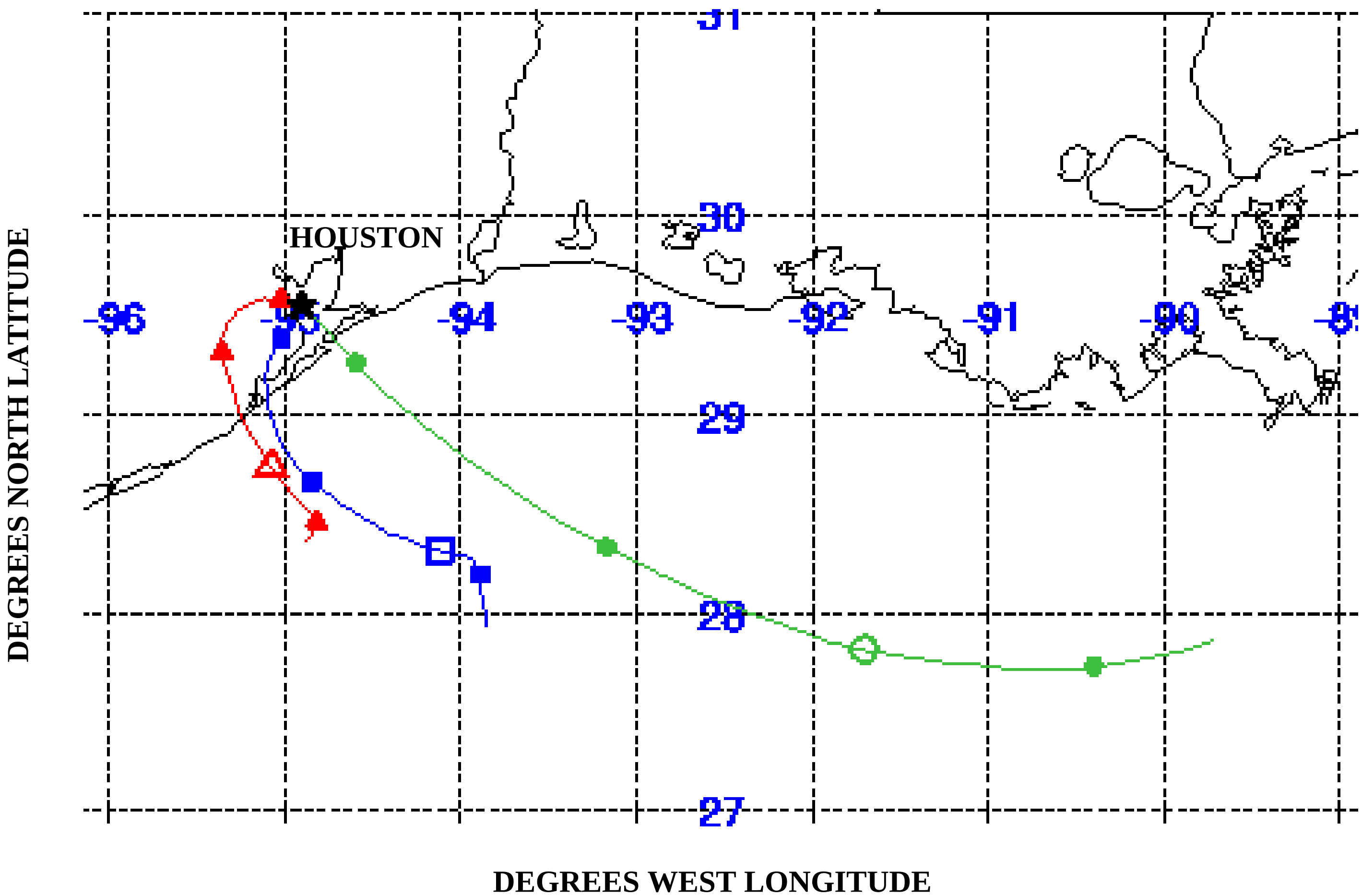


Figure 5-16. Twenty-four-hour back-trajectories for 140 m agl (red line), 700 m agl (blue line), and 1500 m agl (green line) from the general flight area in Houston on August 19, 2000, at 0800 CST.

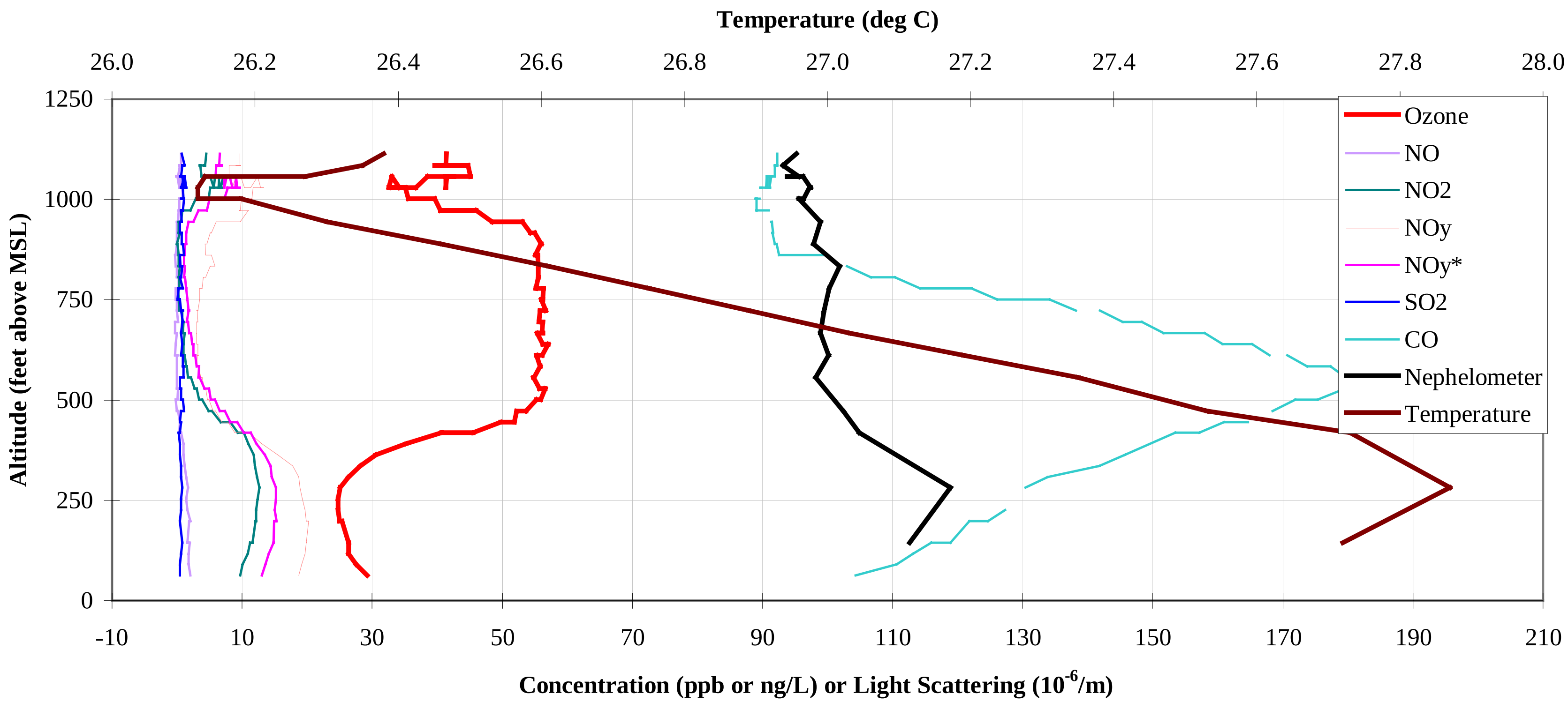


Figure 5-17. Vertical profile of air quality and temperature data collected over Trinity Bay, Texas from 0713 to 0715 CST on August 19, 2000.

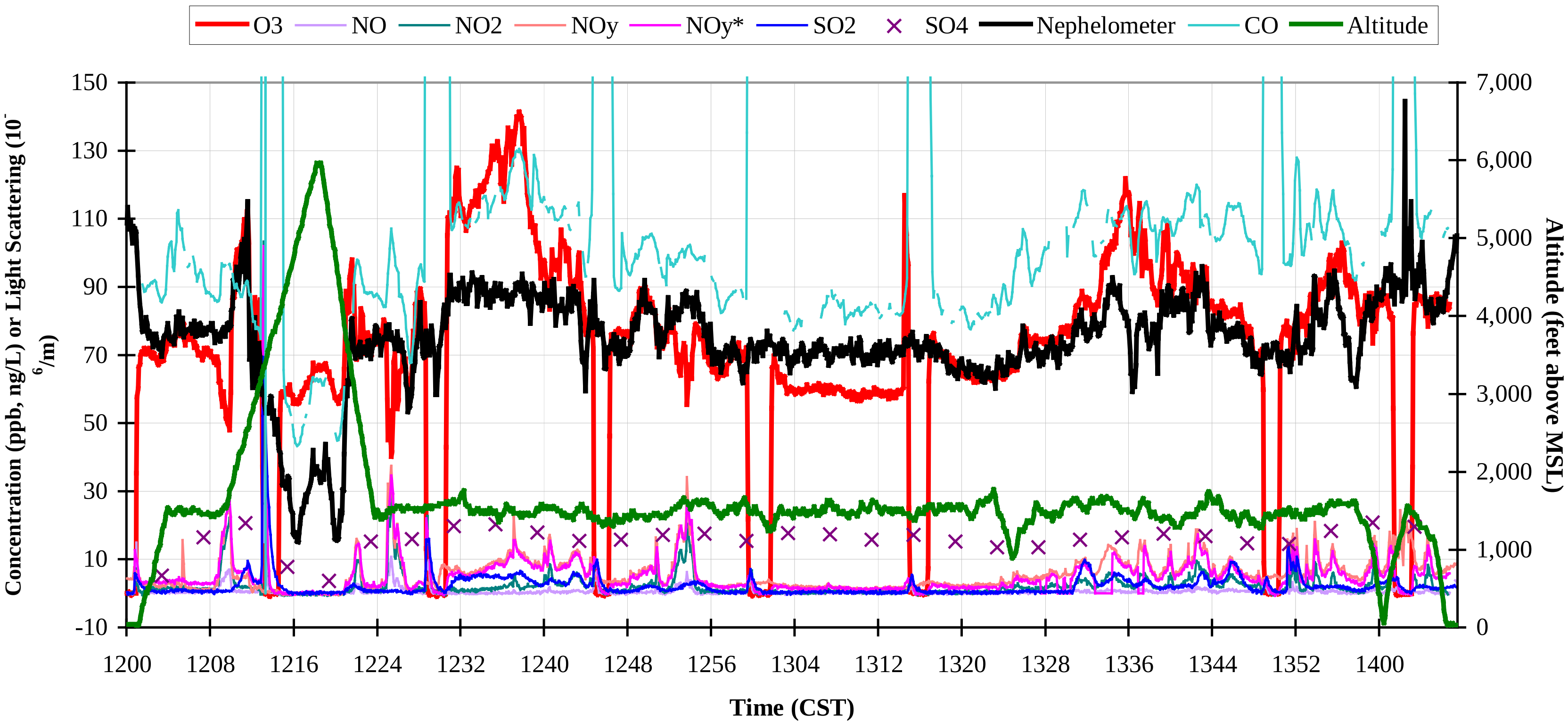


Figure 5-18. Time-series plot of air quality data collected from 1200 to 1410 CST on August 19, 2000.

5.3 FLIGHT 137A AND 137B, AUGUST 21, 2000

On August 21, 2000, there was a morning and an afternoon flight. The morning flight consisted of a series of box climbs up to approximately 2000 ft msl (610 m msl) along with one box climb to 10,000 ft msl (3050 m msl) east of Texas City (**Figure 5-19**). When box climbs were not being flown, the flight altitude was maintained at about 1000 ft msl (305 m msl). The afternoon flight was confined to southeast and central Houston with a single box climb over Galveston Bay and several traverses over eastern Houston near the Ship Channel (**Figure 5-20**). When box climbs and traverses were not being flown, the typical flight altitude was about 1500 ft msl (457 m msl). The flight paths on this day were similar to the flight paths on August 19, 2000.

5.3.1 Overview of Meteorology and Air Quality

There was a broad ridge of high pressure at 500 mb over the southern third of the United States on this day. This feature was observed on the preceding four days as well. The boundary layer depth, as estimated by profiler reflectivity data (C_n^2), was approximately at 984 ft msl (300 m msl) overnight and during the early morning (**Figure 5-21**). The convective boundary layer increased beginning at 0900 CST (1500 UTC) before peaking at 4920 ft msl (1600 m msl) by 1200 CST (1800 UTC).

The radar profiler back-trajectories and the EDAS back-trajectories indicate same-day recirculation of air below 1000 m msl (**Figure 5-20**). The recirculation in the lower levels appeared to be a land/sea breeze circulation: southwesterly flow in the morning followed by a few hours of northeasterly flow, and then easterly flow in the afternoon (**Figure 5-22**). Above 1000 m msl, the radar profiler and EDAS back-trajectories show southeasterly flow changing to easterly by afternoon.

The recirculation in the lowest 3280 ft msl (1000 m msl) combined with the limited vertical mixing allowed for widespread high ozone concentrations as observed at surface CAMS sites and by the aircraft. The highest surface ozone concentration was 159 ppb at CAMS 81 at 1300 CST, and six CAMS sites located in central Houston reported ozone concentrations higher than 140 ppb (not shown). In general, the sites on the east side of Houston had peak ozone concentrations early in the afternoon, while sites on the west side had peak ozone concentrations later in the afternoon. The highest concentration was 178 ppb, observed by the aircraft at 1500 ft msl (457 m msl) just north of the Ship Channel at 1343 CST (Figure 5-20 and **Figure 5-23**). This general ozone layer coincided with high NO_y and SO_2 concentrations.

5.3.2 Characteristics of Ozone and NO_x

Morning Horizontal

- Aloft ozone concentrations during aircraft traverses at approximately 1000 ft msl (305 m msl) were typically less than 40 ppb (see Figure 5-19).
- As shown in **Figure 5-24**, ozone concentrations of 60 to 70 ppb were observed in a layer between 3000 and 10,000 ft msl (915 and 3050 m msl) during a morning box climb east

of Texas City above the morning mixed layer. The 24-hr EDAS back-trajectories indicate that the air at these levels came off the Gulf of Mexico and Louisiana overnight (**Figure 5-25**).

- During the early morning hours, surface ozone concentrations were titrated at most sites, with ozone concentrations ranging from 0 to 30 ppb. Morning NO_x concentrations ranged from 60 to 95 ppb at CAMS 01, CAMS 403 (near the Ship Channel), and CAMS 08 (just north of central Houston) to near zero at outlying sites such as CAMS 26 (northwest of Houston).

Morning Vertical

- Although the structure of the pollutant concentrations varied between morning box climbs at different locations, a given box climb can also show several different pollutant layers and inversions. An example of such a box climb can be seen in **Figures 5-26 and 5-27** representing the La Porte box climb. As shown in Figure 5-26, there was a temperature inversion at 500 ft msl (152 m msl) indicating the top of the nighttime inversion, a second temperature inversion at 1000 ft msl (305 m msl), and a third inversion (Figure 5-27) at about 1500 ft msl (457 m msl).
  - Beneath the nighttime inversion, ozone concentrations were less than 10 ppb due to titration. Just above the inversion, there was a layer of NO_y (60 ppb at 500 ft msl or 152 m msl) and NO (35 ppb at 400 ft msl or 122 m msl) with low ozone concentrations (5 ppb at 500 ft msl or 152 m msl).
  - Above approximately 600 ft msl (183 m msl), NO_y and NO concentrations decreased, and ozone concentrations increased to 30 to 40 ppb.
  - A slight increase in ozone concentrations from 30 to 40 ppb occurred above the third inversion at 1500 ft msl (457 m msl).
- There was a deep morning ascending and descending box climb over Galveston Bay. As shown in **Figure 5-28**, the descending profile indicated a layer of high NO_y concentrations (35 ppb), SO_2 concentrations of 25 ppb, and NO concentrations of 7 ppb at 1800 ft msl (550 m msl) that were not present in the ascending profile, indicating that this was probably a small, localized layer. Ozone concentrations at this level in the descending profile were around 25 ppb and increased to 40 ppb just above the inversion at 2000 ft msl (610 m msl). Above the inversion, ozone concentrations increased to 70 ppb at 3000 ft msl (915 m msl), which was characteristic of the large-scale air-mass over Houston. Above 3000 ft msl (915 m msl), data from the ascending and descending profiles agreed.

Afternoon Horizontal

- As discussed above, surface ozone concentrations peaked on the east side of Houston at around 1300 CST and on the west side of Houston at around 1500 CST. The observed recirculation (Figure 5-20) resulted in widespread surface concentrations in excess of 100 ppb. An easterly flow developed around 1200 CST, which transported ozone to the west. Clouds associated with thunderstorms in the region were observed in the visible satellite imagery to have moved over the area, beginning at 1400 CST and moving from east to west (**Figure 5-29**).

- In **Figure 5-30**, the general locations of a series of traverses flown near the Ship Channel are shown as A, B, C, and D. **Table 5-1** shows the pollutant concentrations in those traverses (see Figures 5-20 and 5-30).

Table 5-1. Two- to five-minute average pollutant concentrations found in a series of traverses flown over Houston, Texas, on August 21, 2000, from 1206 to 1417 CST.

Pass	Time (CST)	Ozone Concentration (ppb)	NO_y Concentration (ppb)	SO_2 Concentration (ppb)
A (Chambers County)	1245	100	7	3
B (Deer Park/Pasadena)	1251	150	55	20
C (West Houston)	1340	180	25	15
D (Central Houston)	1400	135	20	10

- In all of the above segments, NO concentrations were near 0 ppb, indicating that these air parcels did not contain fresh emissions.
- Radar profiler winds were easterly from 1100 to 1600 CST from the surface to around 6565 ft msl (2000 m msl) (Figure 5-22), and the air quality observations in these passes were consistent with the winds.
  - The highest concentration of ozone (180 ppb) observed during the four segments was found at pass C, the western-most segment. SO_2 and NO_y concentrations in pass C were 15 and 25 ppb, respectively.
  - The lowest ozone concentrations (100 ppb) were observed at pass A (the eastern-most segment). SO_2 and NO_y concentrations in pass B were 3 and 7 ppb, respectively.
  - Passes B and D, the central segments, had similar ozone concentrations of 150 and 135 ppb, respectively. However, the highest NO_y and SO_2 concentrations of all four segments were along pass B at 55 and 20 ppb, respectively.
- A layer with NO_y and SO_2 concentrations of 40 and 40 ppb, respectively, was observed at 1402 CST just south of pass D. Ozone concentrations at this location were titrated to 60 ppb while NO concentrations were 10 ppb.

Afternoon Vertical

- The only box climb during the afternoon flight shows that ozone concentrations over Galveston Bay were 55 to 65 ppb throughout the depth of the box climb (**Figure 5-31)**. These concentrations were similar to the aloft concentrations measured during the morning. Concentrations of NO_y were 2 to 3 ppb and NO and SO_2 concentrations were near 0 ppb.

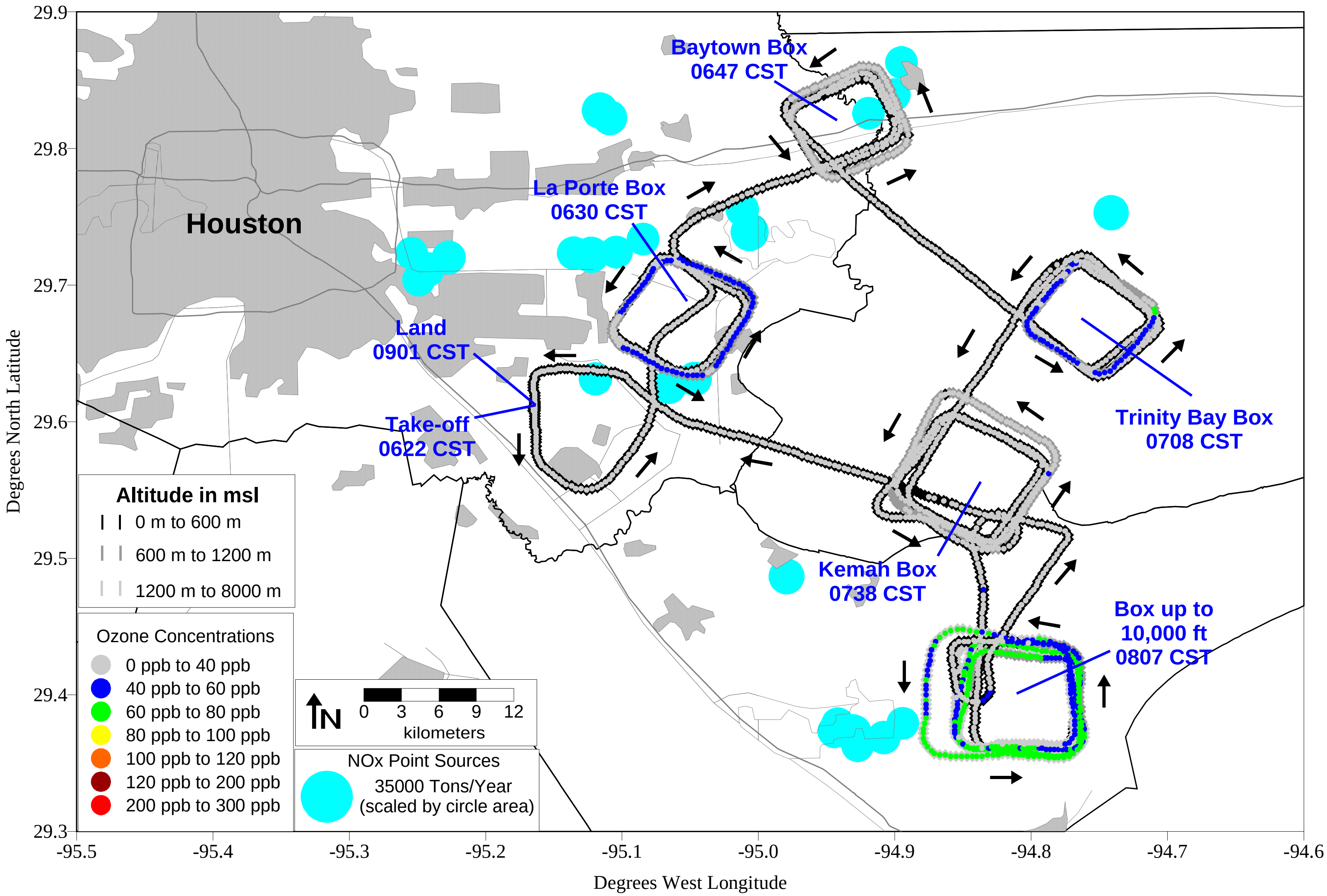


Figure 5-19. Flight 137 flight position, altitude, and aloft ozone concentrations on the morning of August 21, 2000.

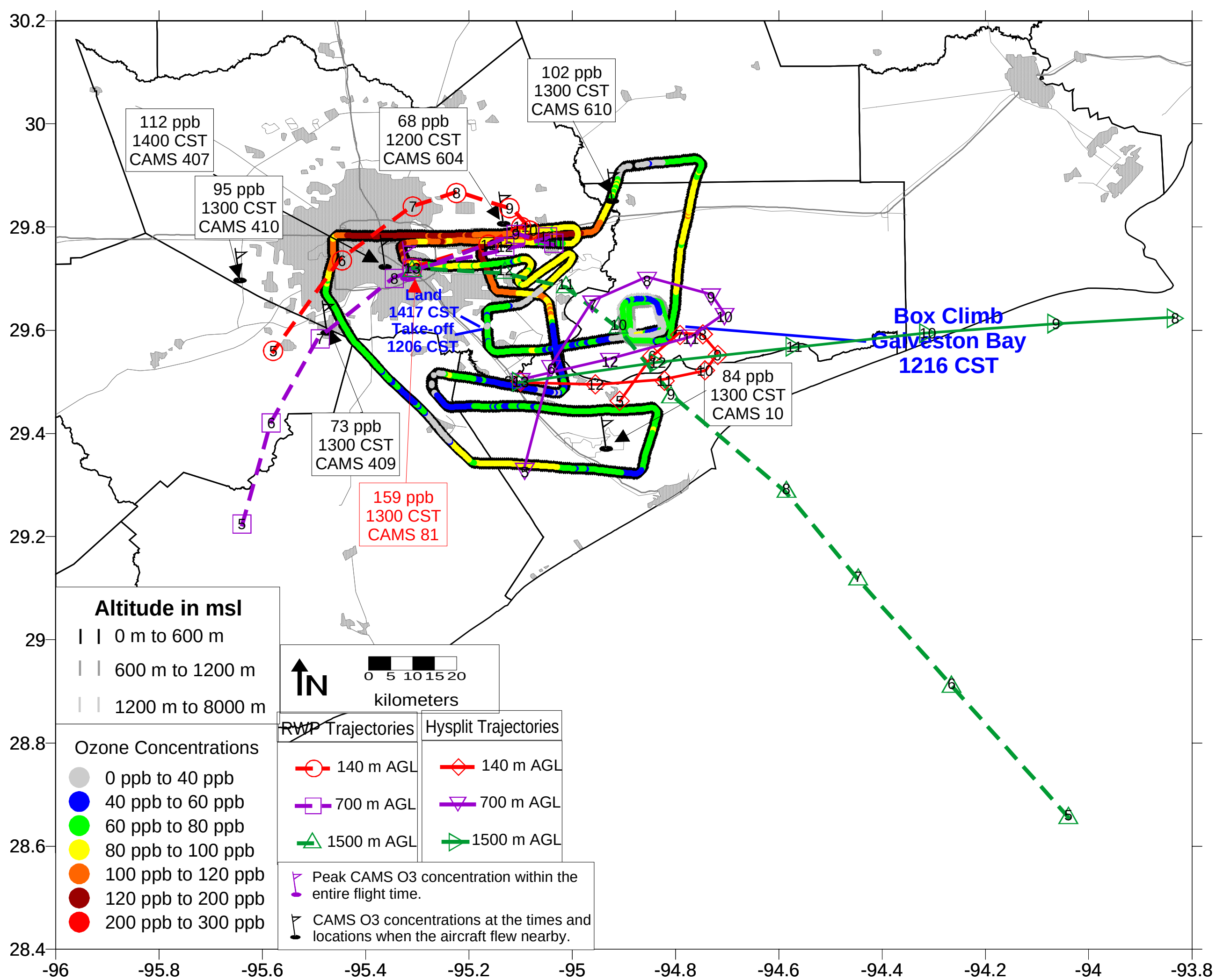


Figure 5-20. Flight 137 flight position, altitude, aloft ozone concentrations, CAMS surface ozone concentrations, and back-trajectories on the afternoon of August 21, 2000.

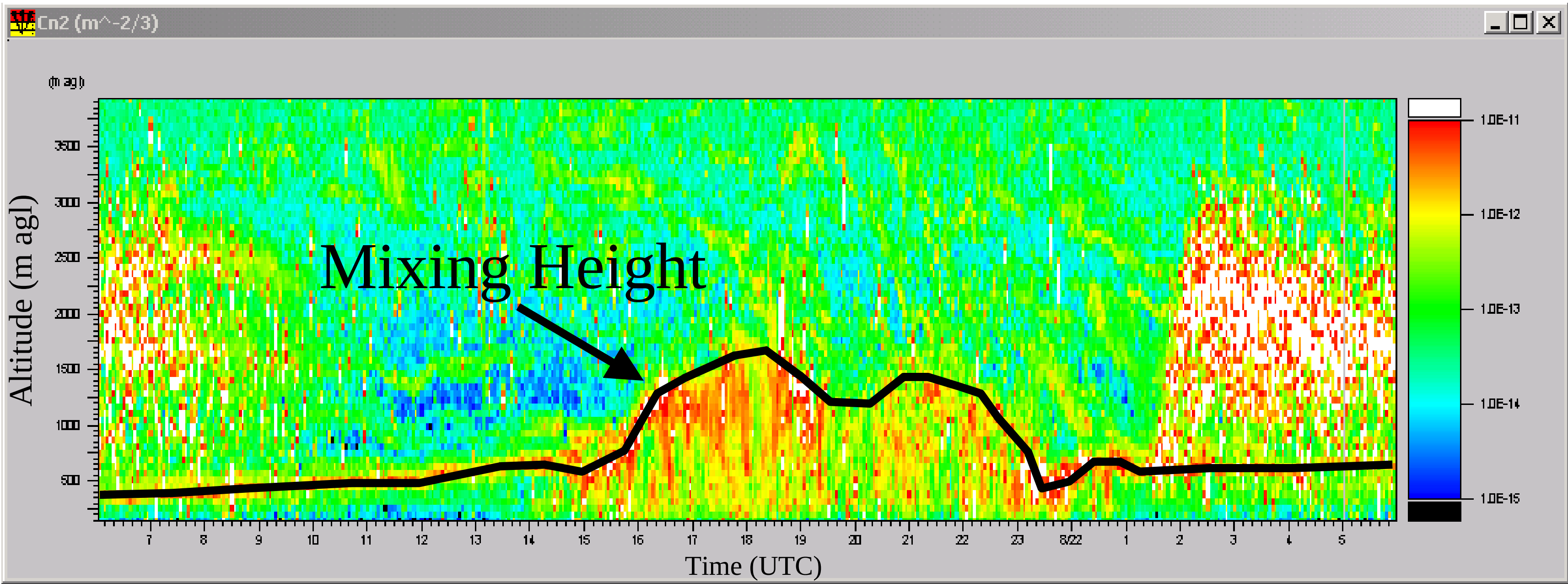


Figure 5-21. Radar wind profiler reflectivity data (C_n^2) and estimated mixing height for August 21, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

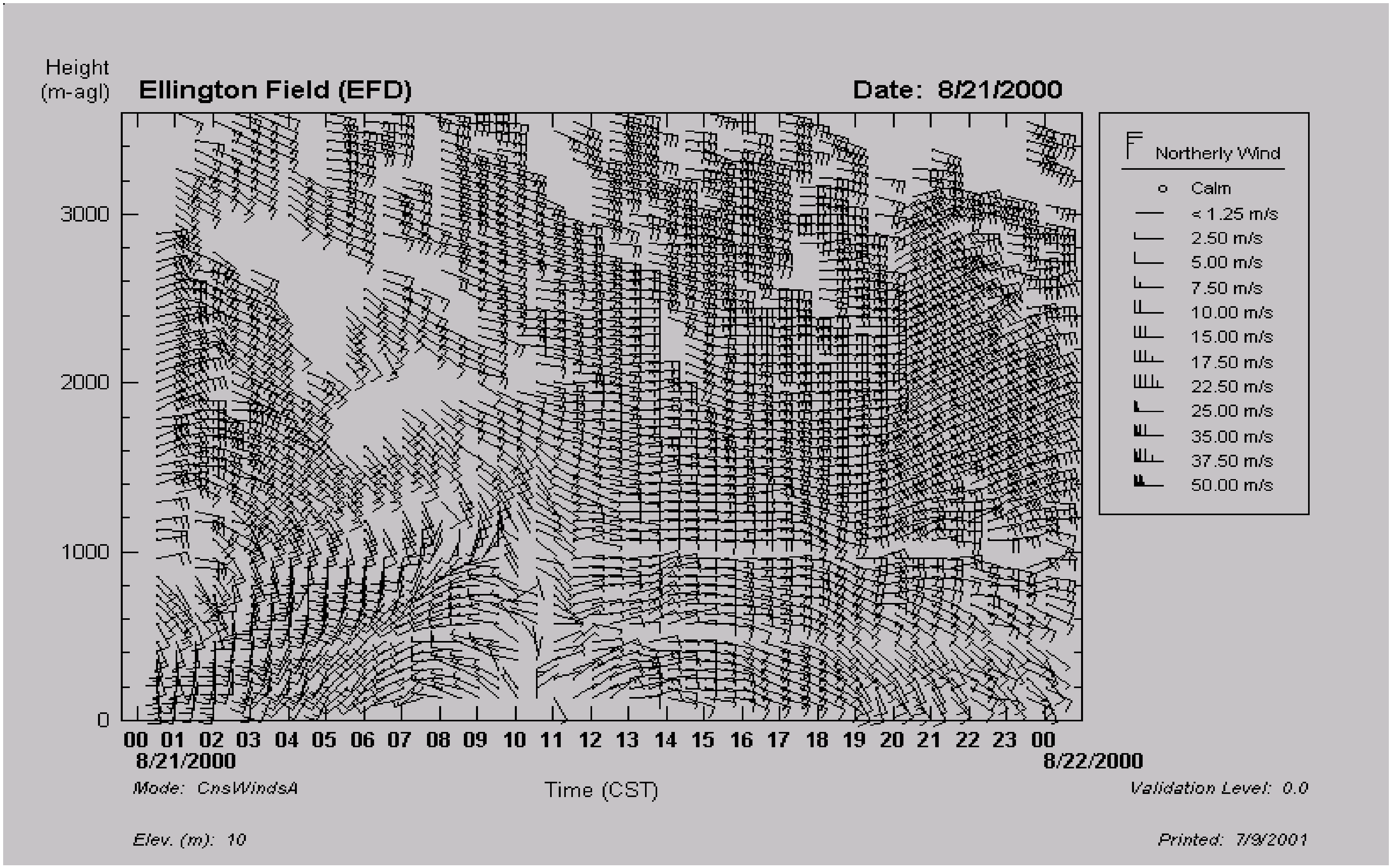


Figure 5-22. Radar wind profiler data for August 21, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

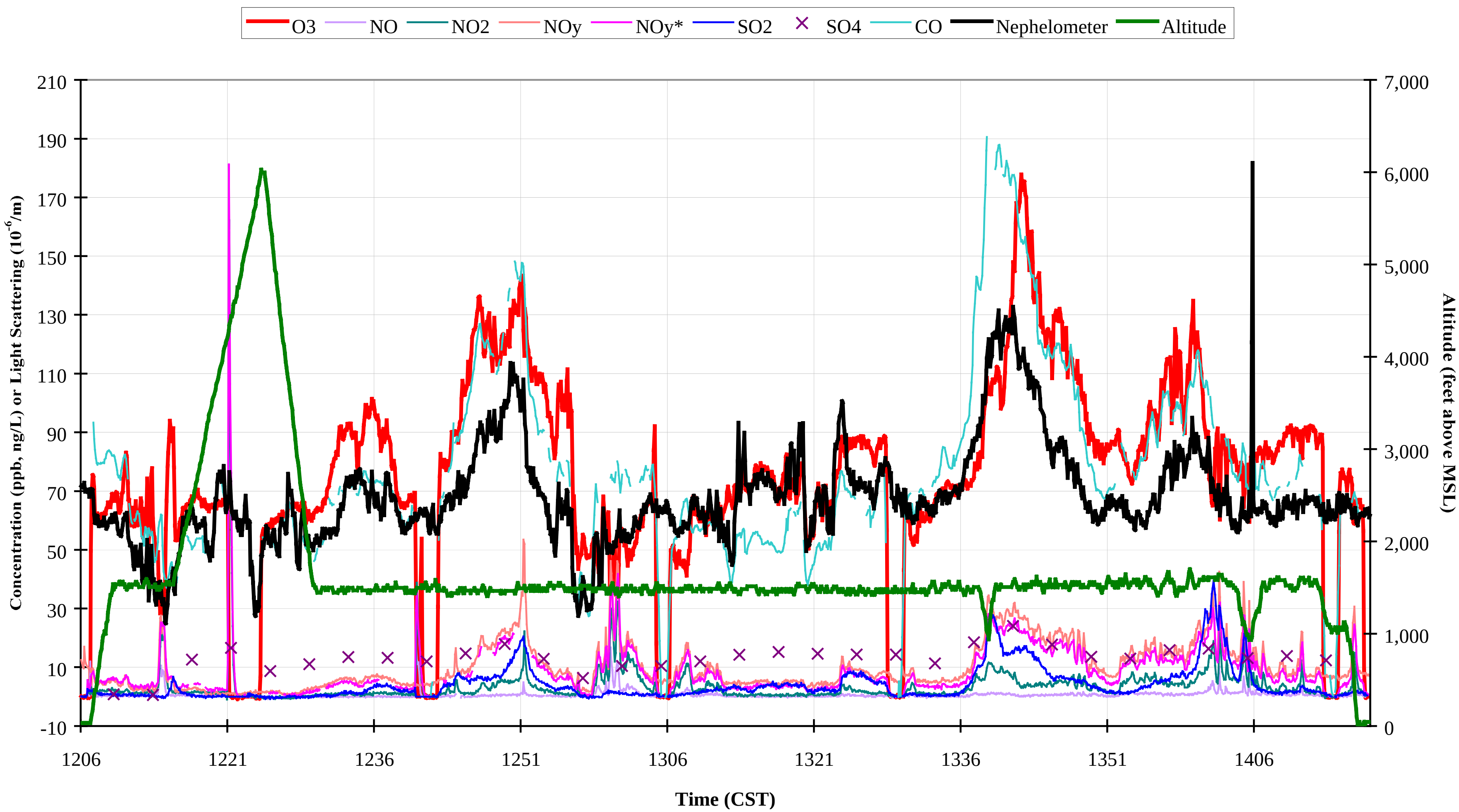


Figure 5-23. Time-series plot of air quality data collected from 1206 to 1417 CST on August 21, 2000.

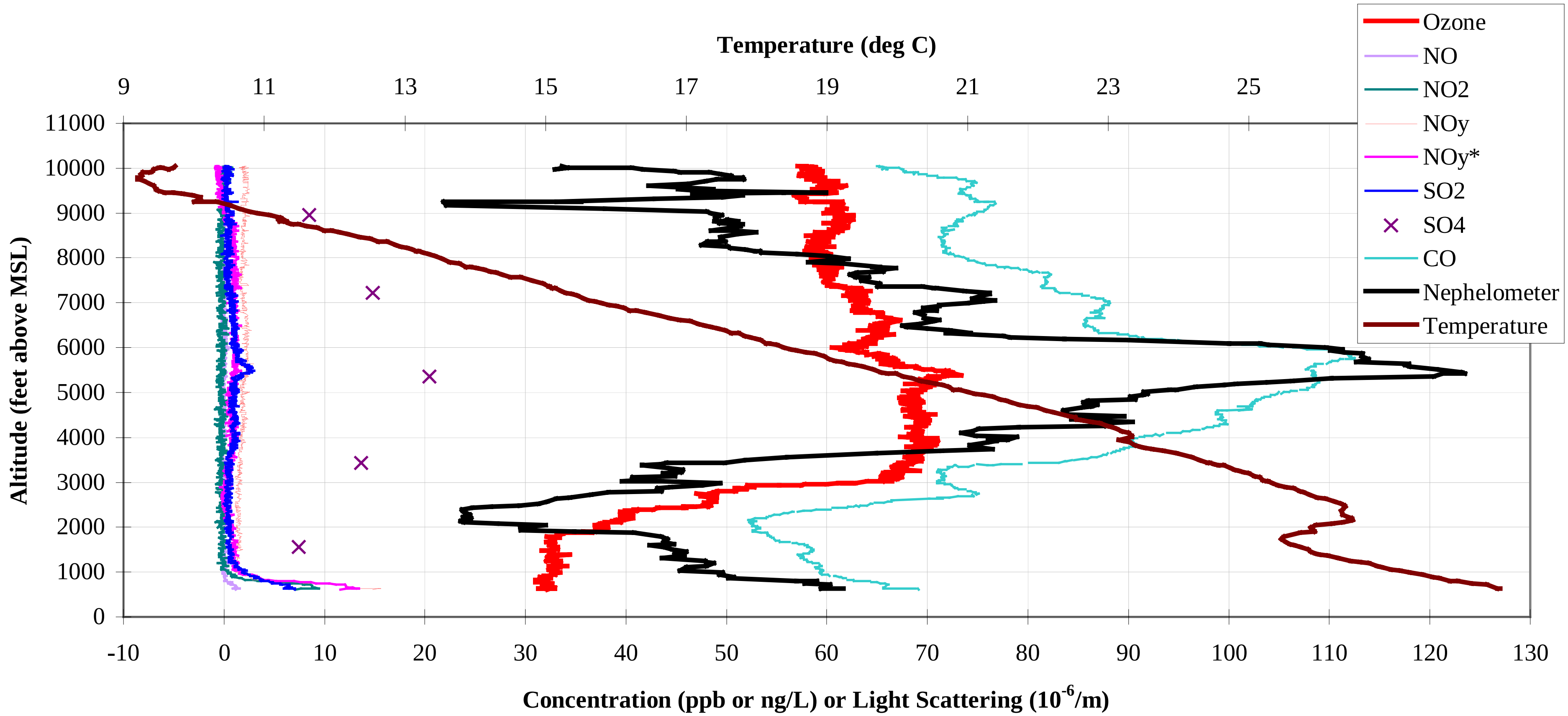


Figure 5-24. Vertical profile of air quality and temperature data collected over Galveston Bay (east of Texas City) from 0806 to 0828 CST on August 21, 2000.

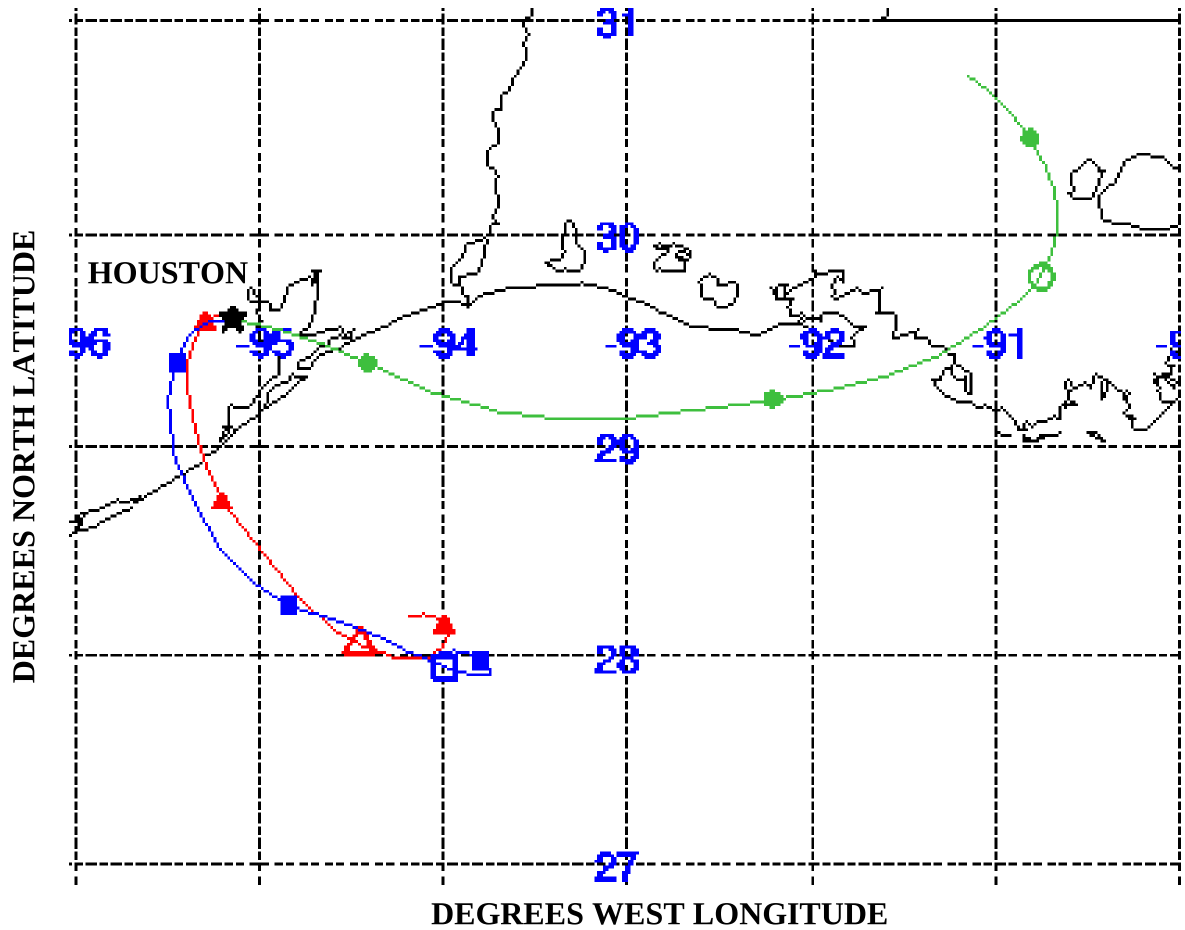


Figure 5-25. Twenty-four-hr back-trajectories for 140 m agl (red line), 700 m agl (blue line), and 1500 m agl (green line) from the general flight area in Houston on August 21, 2000, at 0900 CST.

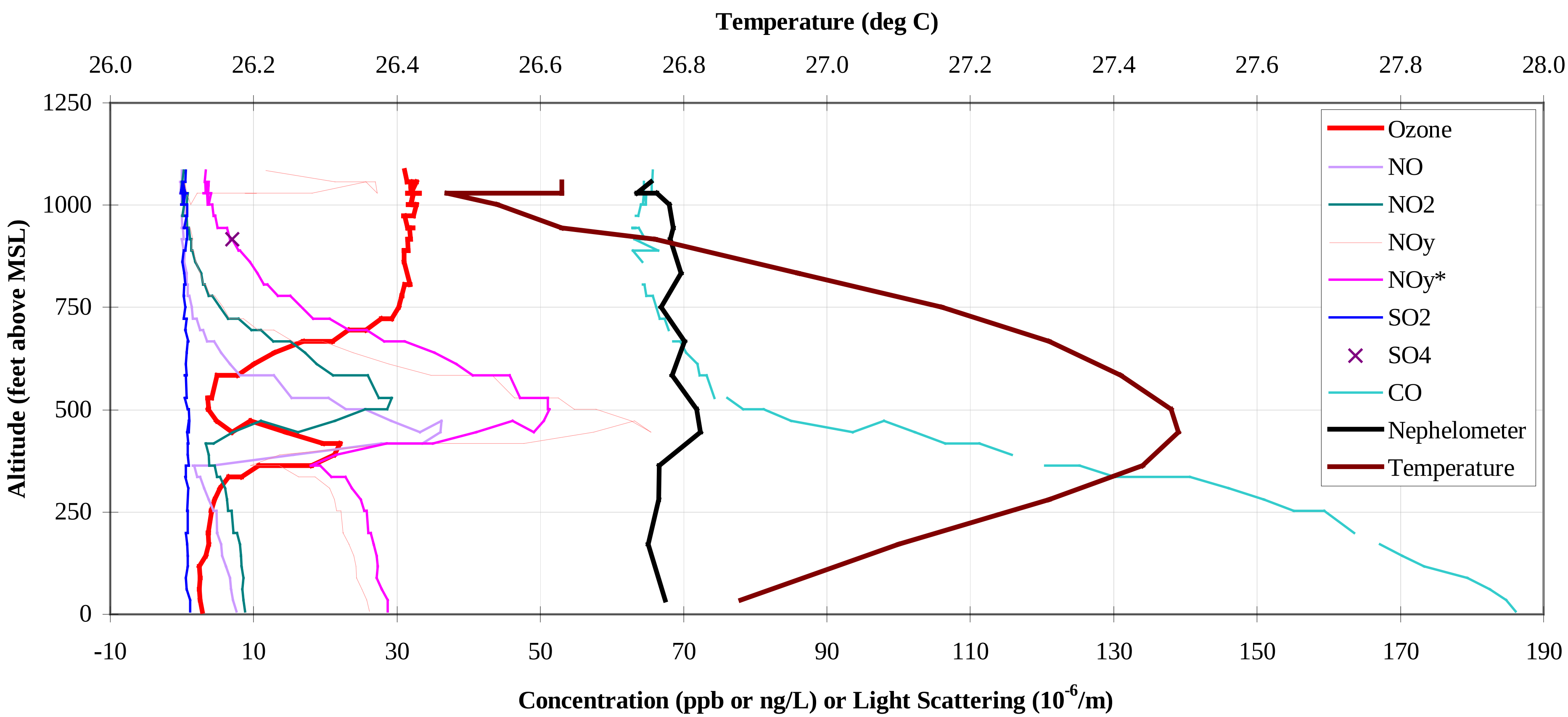


Figure 5-26. Vertical profile of air quality and temperature data collected over La Porte, Texas from 0627 to 0643 CST on August 21, 2000.

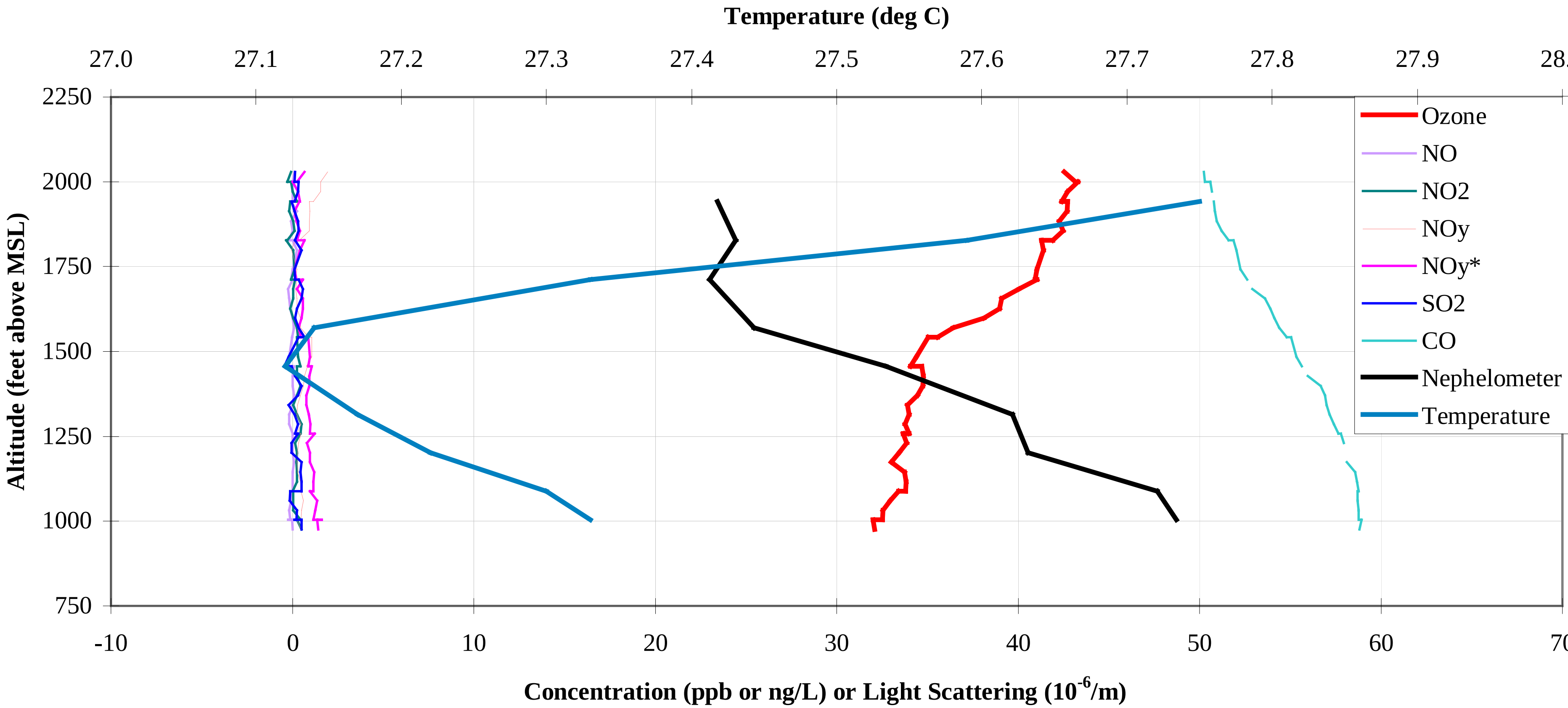


Figure 5-27. Vertical profile of air quality and temperature data collected over La Porte, Texas, from 0643 to 0644 CST on August 21, 2000.

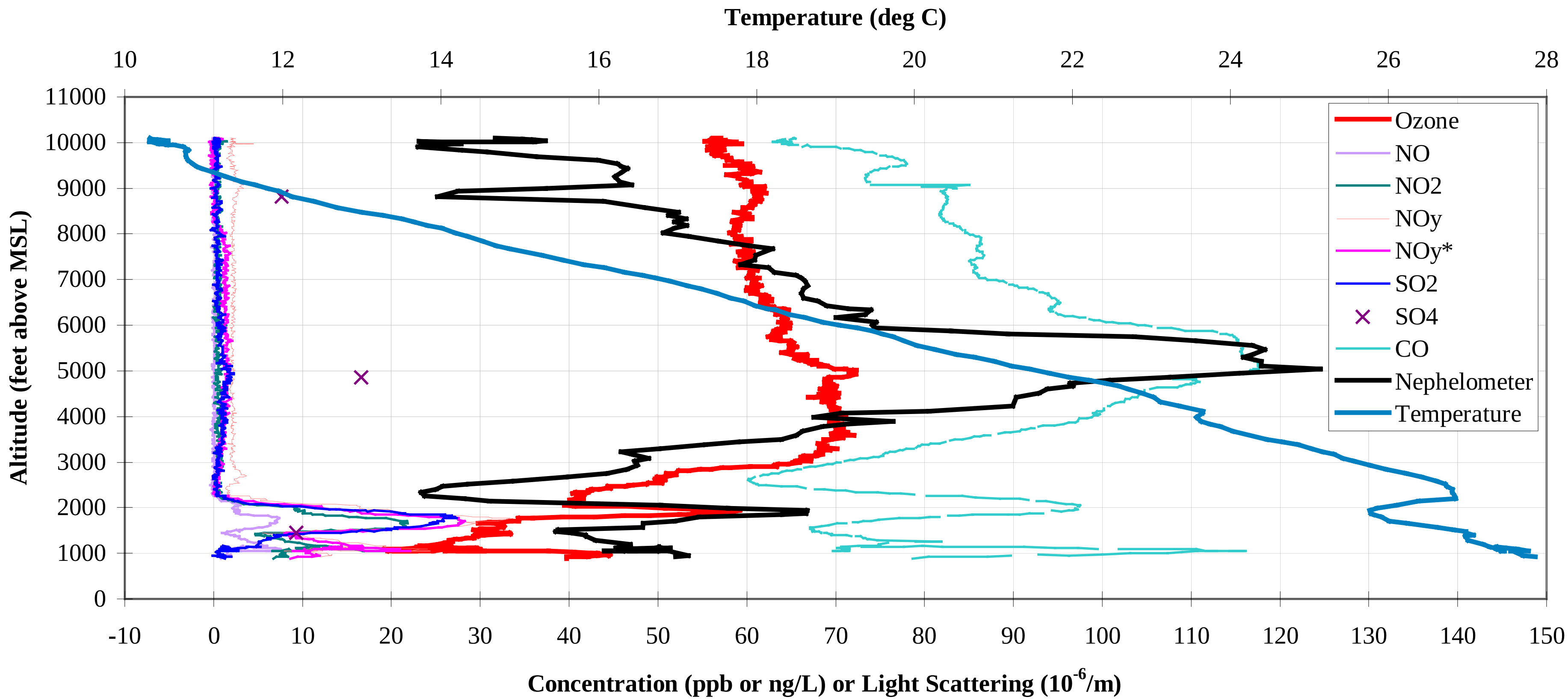


Figure 5-28. Vertical profile of air quality and temperature data collected over Galveston Bay, Texas, from 0834 to 0847 CST on August 21, 2000.

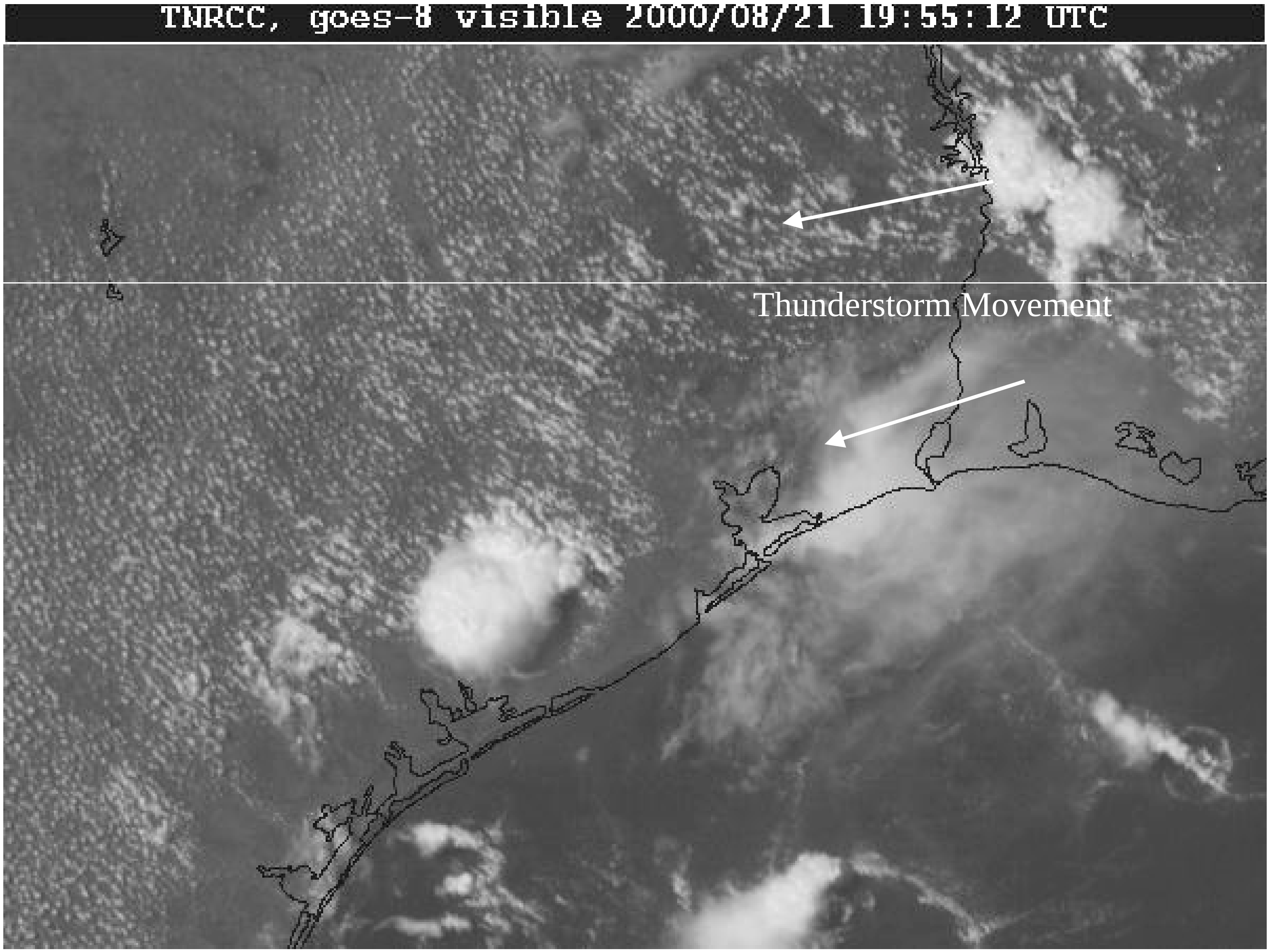


Figure 5-29. Visible satellite imagery at 1355 CST (1955 UTC) on August 21, 2000.

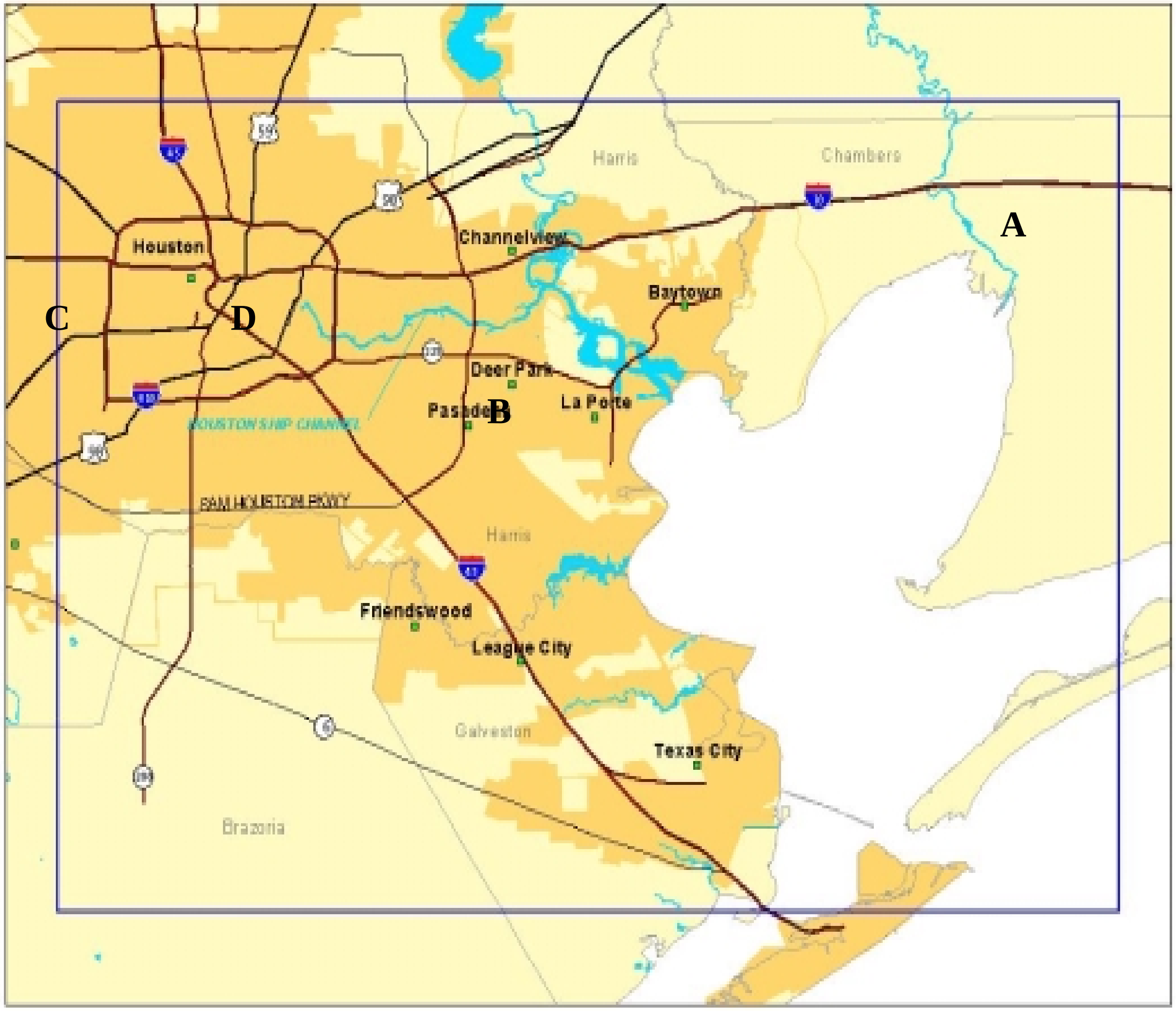


Figure 5-30. General locations of select flight traverses from 1206 to 1417 CST over Houston, Texas, on August 21, 2000.

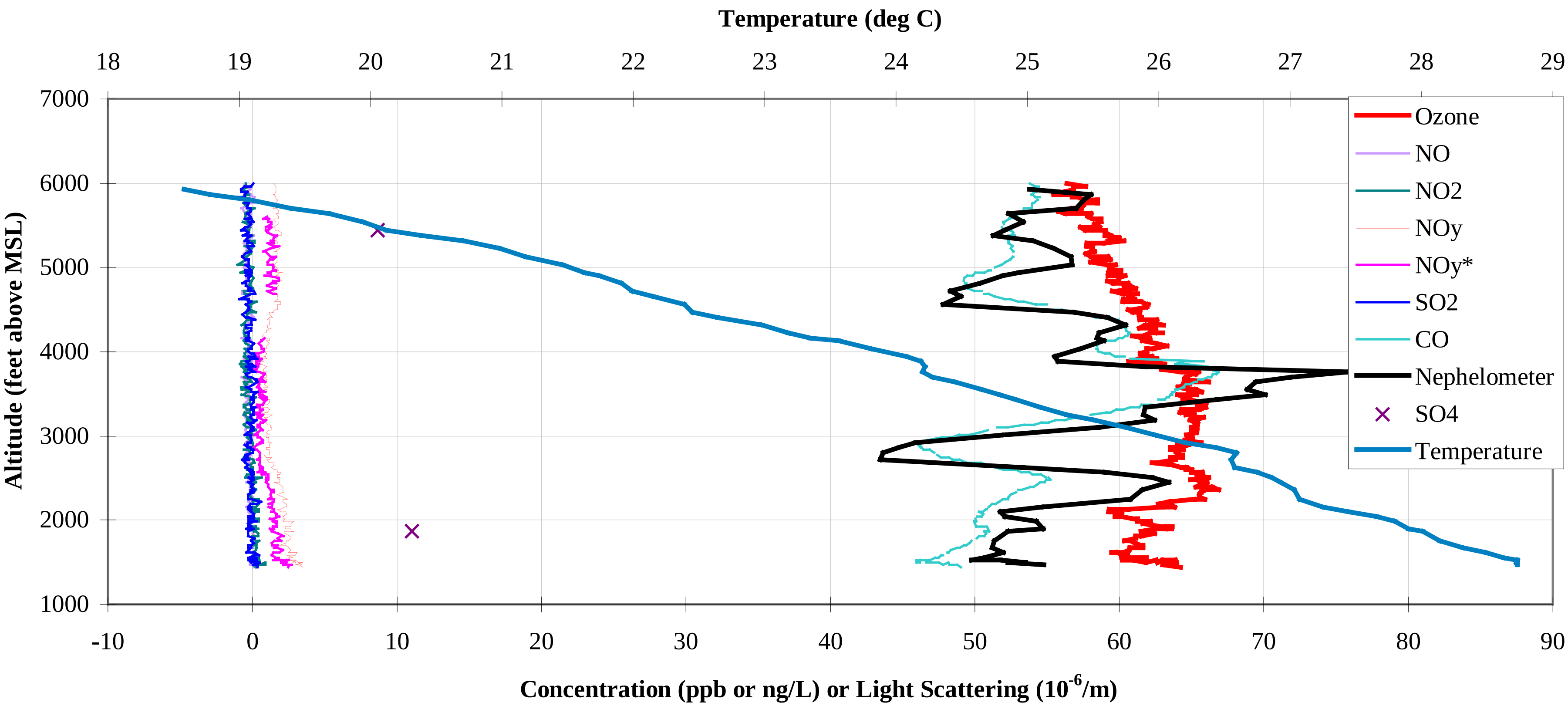


Figure 5-31. Vertical profile of air quality and temperature data collected over Galveston Bay, Texas, from 1224 to 1231 CST on August 21, 2000.

5.4 FLIGHT 140, AUGUST 25, 2000

On August 25, 2000, there was one flight beginning at 1052 CST and ending at 1338 CST. Unlike previous flight patterns, this one began with a semi-circular arc northeast of Houston, followed by a northerly path to a point well north of Houston, then a return southerly path back to complete the semi-circular arc. Prior to landing, a series of transects were flown over the Ship Channel and central Houston (**Figure 5-32**). The typical flight altitude was 1500 ft msl (457 m msl) with the exception of the flight north of Houston, which ascended to approximately 3000 ft msl (915 m msl).

5.4.1 Overview of Meteorology and Air Quality

The synoptic pattern over Houston shown in **Figure 5-33a** (0600 CST August 25, 2000) included a broad ridge of high pressure at 500 mb over the southern third of the United States. No anticyclonic circulation was evident as had been on August 21, 2000. At the surface there was very little pressure gradient (**Figure 5-33b**), which allowed for land/sea breeze circulation to dominate.

The mixing height as estimated by profiler reflectivity data (C_n^2) at Ellington Field was indistinguishable overnight and during the early morning (**Figure 5-34**). From about 0800 to 1030 CST (1400 to 1630 UTC) the mixing height increased from 1640 to 3280 ft msl (500 to 1000 m msl). The mixing height then rapidly increased to 6560 ft msl (2000 m msl) at 1130 CST (1730 UTC) then decreased to around 3250 ft msl (1000 m msl) by 1400 CST (2000 UTC) before increasing to around 4920 ft msl (1500 m msl) at 1530 CST (2130 UTC). The mixing heights then declined gradually until the late night hours. The only box climb was flown well north of Houston at 1140 CST. These vertical profiles were flown from 1500 feet msl (457 m msl) to approximately 3000 ft msl (915 m msl) and no temperature inversions were encountered, so the mixing heights north of Houston were probably greater than 3000 ft msl (915 m msl) at 1140 CST.

Within the daytime boundary layer, the winds were lighter than the August 21 episode. The land breeze is shown by the northerly and northeasterly winds from 0600 to 1230 CST in the lowest 1600 ft msl (500 m msl) (**Figure 5-35**). By 1230 CST, the Bay Breeze began and lasted until around 1630 CST, at which time the Gulf Breeze flowed past the radar profiler (Figure 5-35). Both the radar profiler and EDAS back-trajectories show the land/sea breeze recirculation at the lower back-trajectory levels (140 and 700 m agl) while the upper-level back-trajectories (1500 m agl) show slow northeasterly flow (Figure 5-32). The 24-hr EDAS back-trajectories showed long-range transport from the Gulf of Mexico at all levels (**Figure 5-36**).

5.4.2 Characteristics of Ozone and NO_x

- No morning flight was performed so morning air quality characteristics could not be assessed.
- There were no NO or NO_y concentration measurements made during this flight.

- Peak afternoon ozone concentrations observed by the aircraft were about 205 ppb, observed at 1500 ft msl (457 m msl) over the Ship Channel and central Houston at 1320 and 1330 CST (Figure 5-32 and **Figure 5-37**). These peaks are within the easterly flow observed at Ellington Field by the radar wind profiler just after the onset of the Bay Breeze (Figure 5-35). The peaks were associated with SO_2 concentrations of 10 to 30 ppb. The flight was concluded prior to the onset of the Gulf Breeze.
- Note that when ozone concentrations are shown dropping to zero, calibrations were being performed; and the data recorded during the calibrations were not used in this analysis.
- Peak surface ozone concentration was 194 ppb in the central Houston area at CAMS 407 at 1300 CST. Multiple sites in central Houston reported surface ozone concentrations greater than 150 ppb.
- Aloft ozone concentrations were generally similar to surface ozone concentrations. For example, on the east side of Houston, aloft concentrations at 1300 CST at the traverse altitude of around 1500 ft msl (457 m msl) (Figure 5-32) were 150 to 170 ppb, while the ozone concentrations at nearby CAMS 81 were 185 ppb at 1300 CST (not shown). The aloft ozone observed in the area near CAMS 81 is associated with SO_2 concentrations of up to 30 ppb. Ozone concentrations to the south of Houston were considerably lower. For example, the profile associated with the landing showed ozone concentrations of 70 to 80 ppb from 1000 ft msl (9305 m msl) to the surface at Ellington Field (**Figure 5-38**).
- The consistency between the 1500-ft msl (457-m msl) ozone concentrations and the surface ozone concentrations throughout the flight and in the above example suggests that the atmosphere was well-mixed to at least 1500 ft msl (457 m msl) during the afternoon, which is consistent with the radar profiler peak mixing height of 6560 ft msl (2000 m msl).
- The radar profiler and EDAS back-trajectories both indicate that same-day transport originated over central Houston, moved east during the early morning hours, then moved west during the late morning and early afternoon; therefore, ozone observed east of Houston was probably a combination of central Houston sources and emissions from the Ship Channel area.

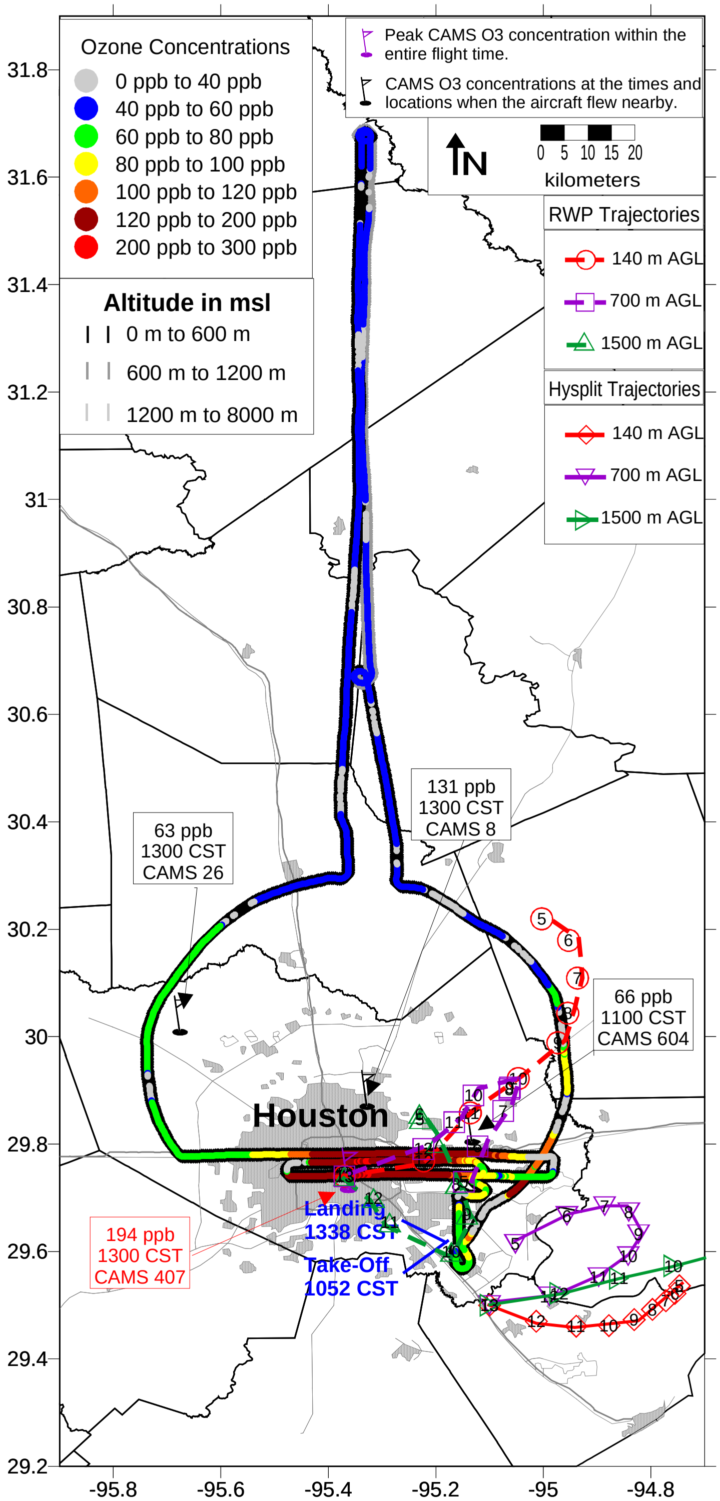


Figure 5-32. Flight 140 flight position, altitude, aloft ozone concentrations, CAMS surface ozone concentrations, and back-trajectories on the afternoon of August 25, 2000.

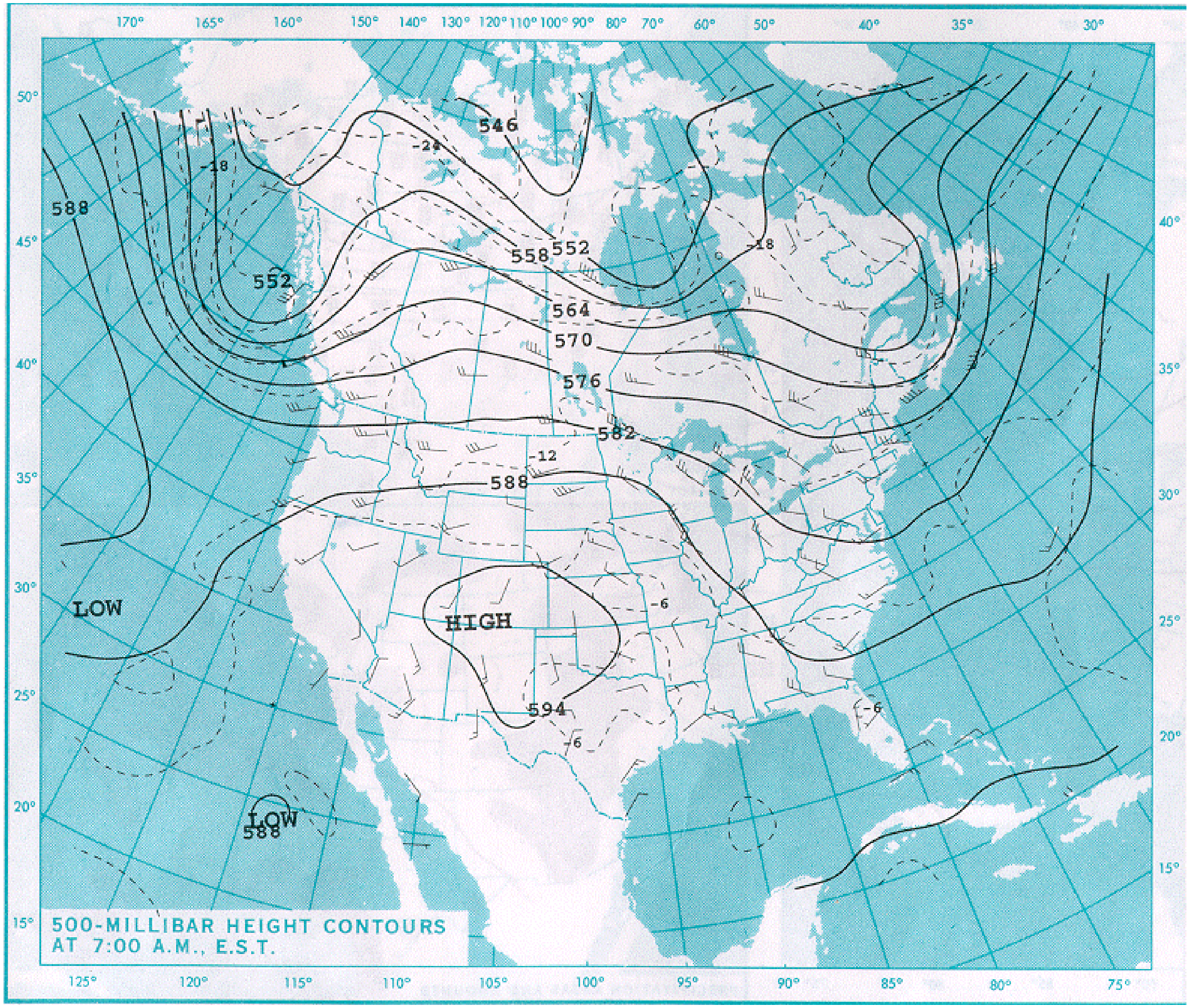


Figure 5-33a. Height contours of the 500-mb pressure surface at 0600 CST on August 25, 2000.

FRIDAY, AUGUST 25, 2000

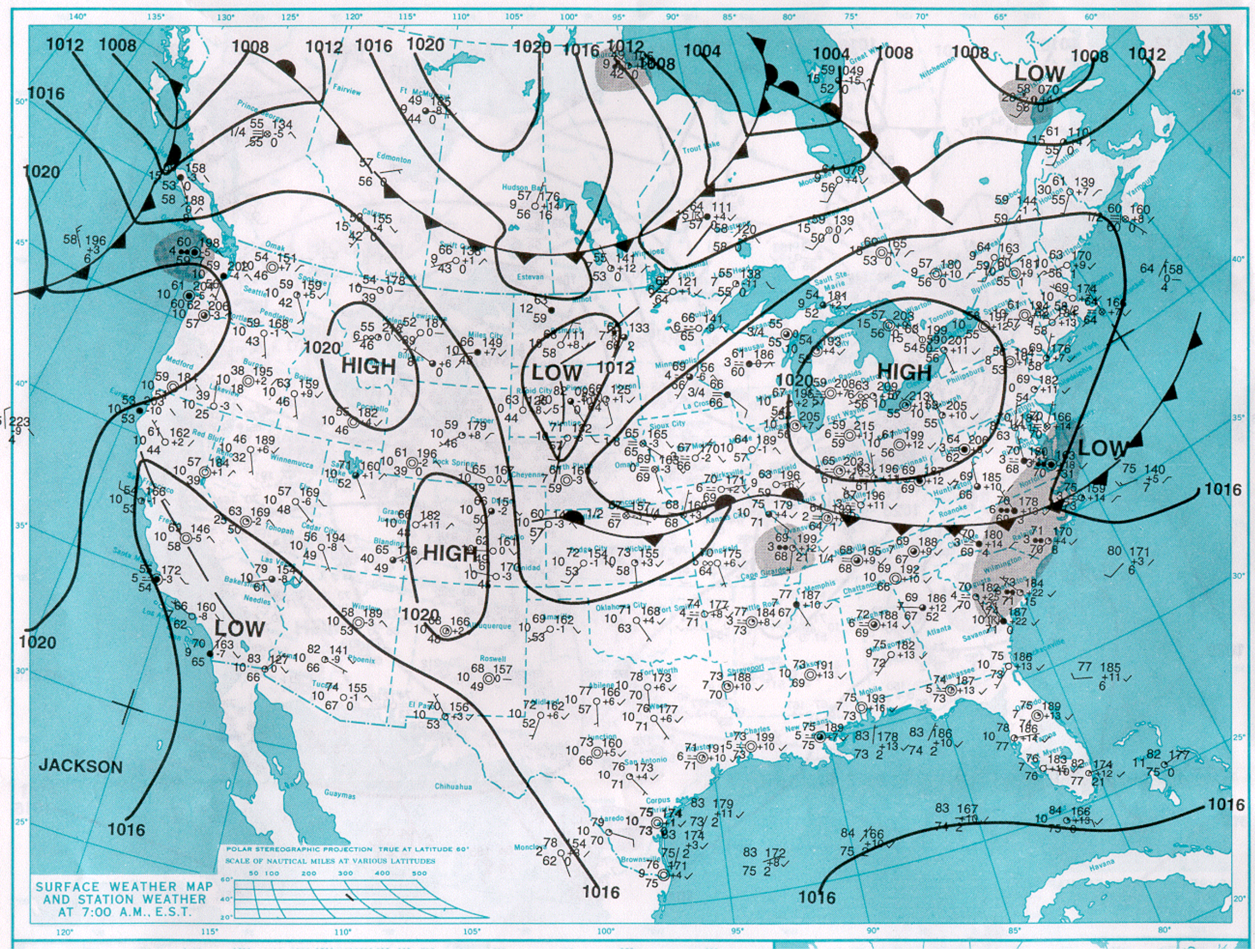


Figure 5-33b. Surface analysis at 0600 CST on August 25, 2000.

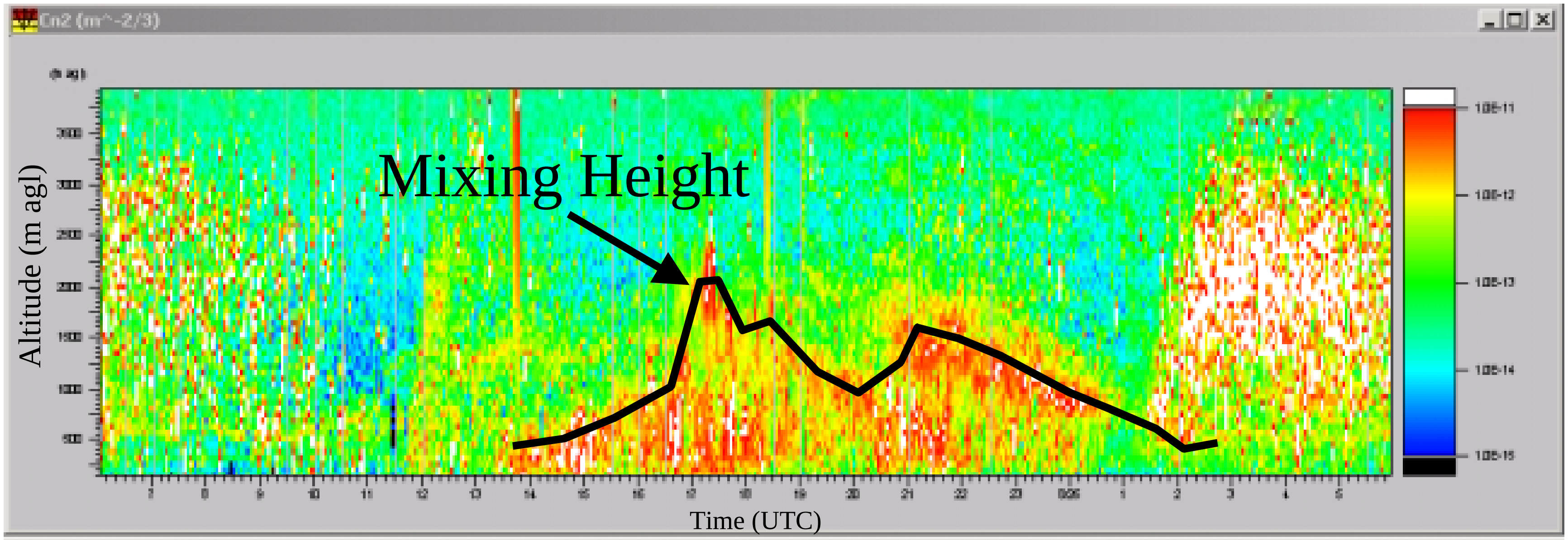


Figure 5-34. Radar wind profiler reflectivity data (C_n^2) and estimated mixing height for August 25, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

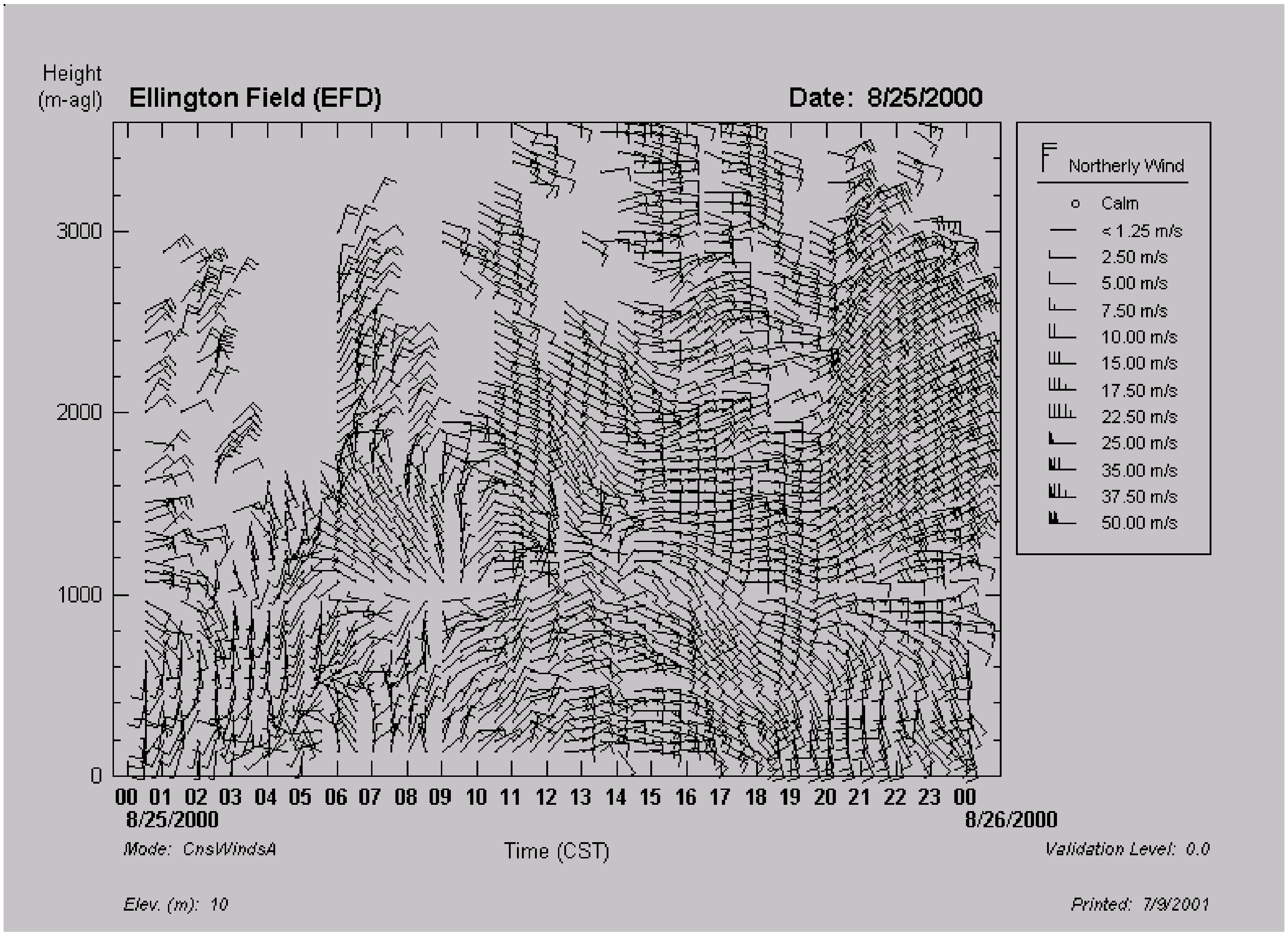


Figure 5-35. Radar wind profiler data for August 25, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

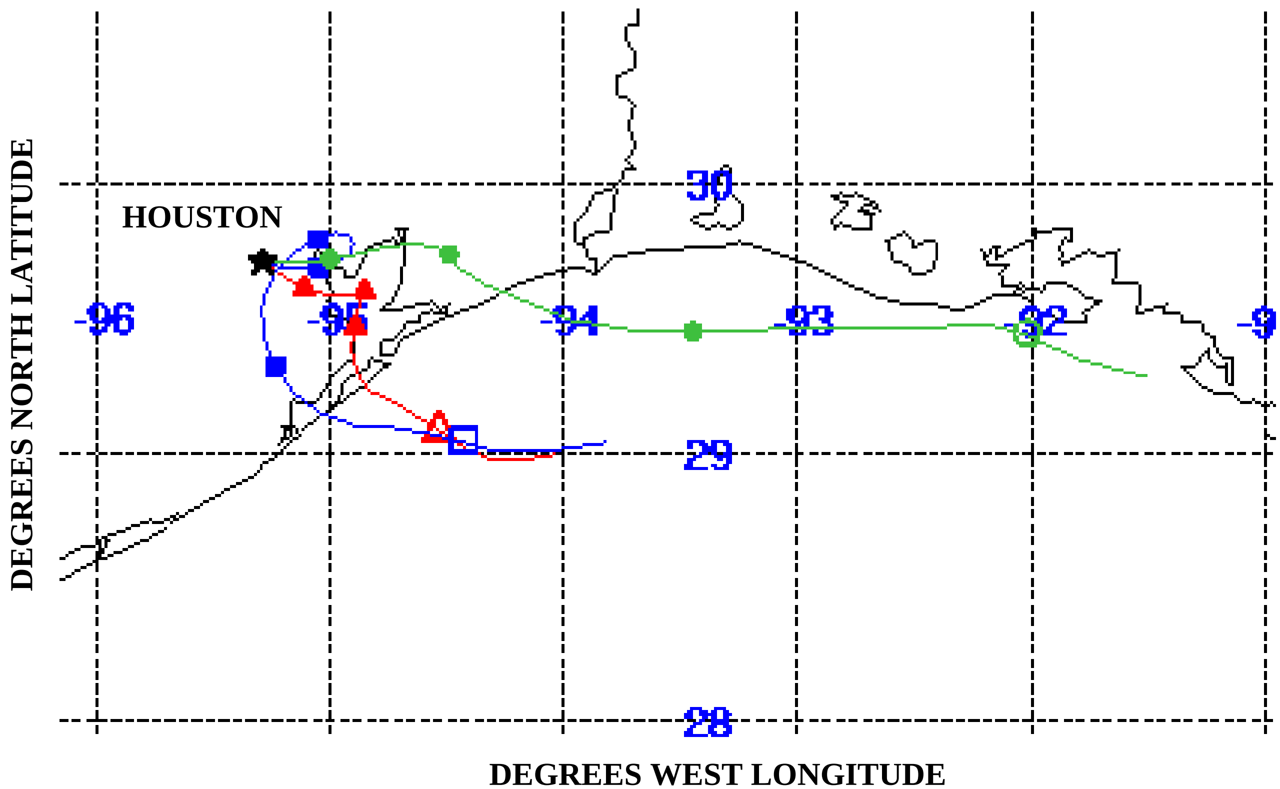


Figure 5-36. Twenty-four-hour back-trajectories for 140 m agl (red line), 700 m agl (blue line), and 1500 m agl (green line) from the general flight area in Houston on August 25, 2000, at 1400 CST.

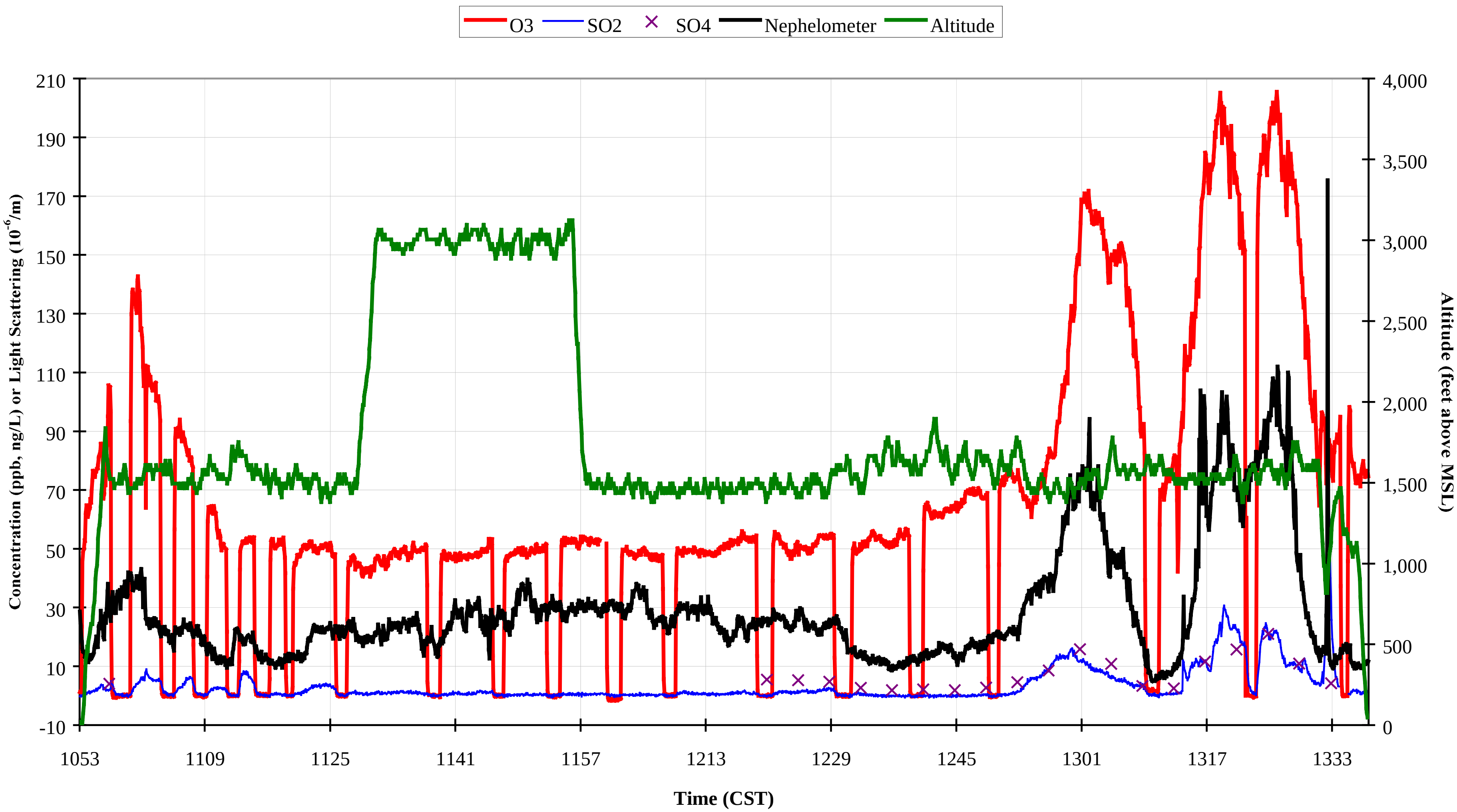


Figure 5-37. Time-series plot of air quality data collected from 1053 to 1340 CST on August 25, 2000.

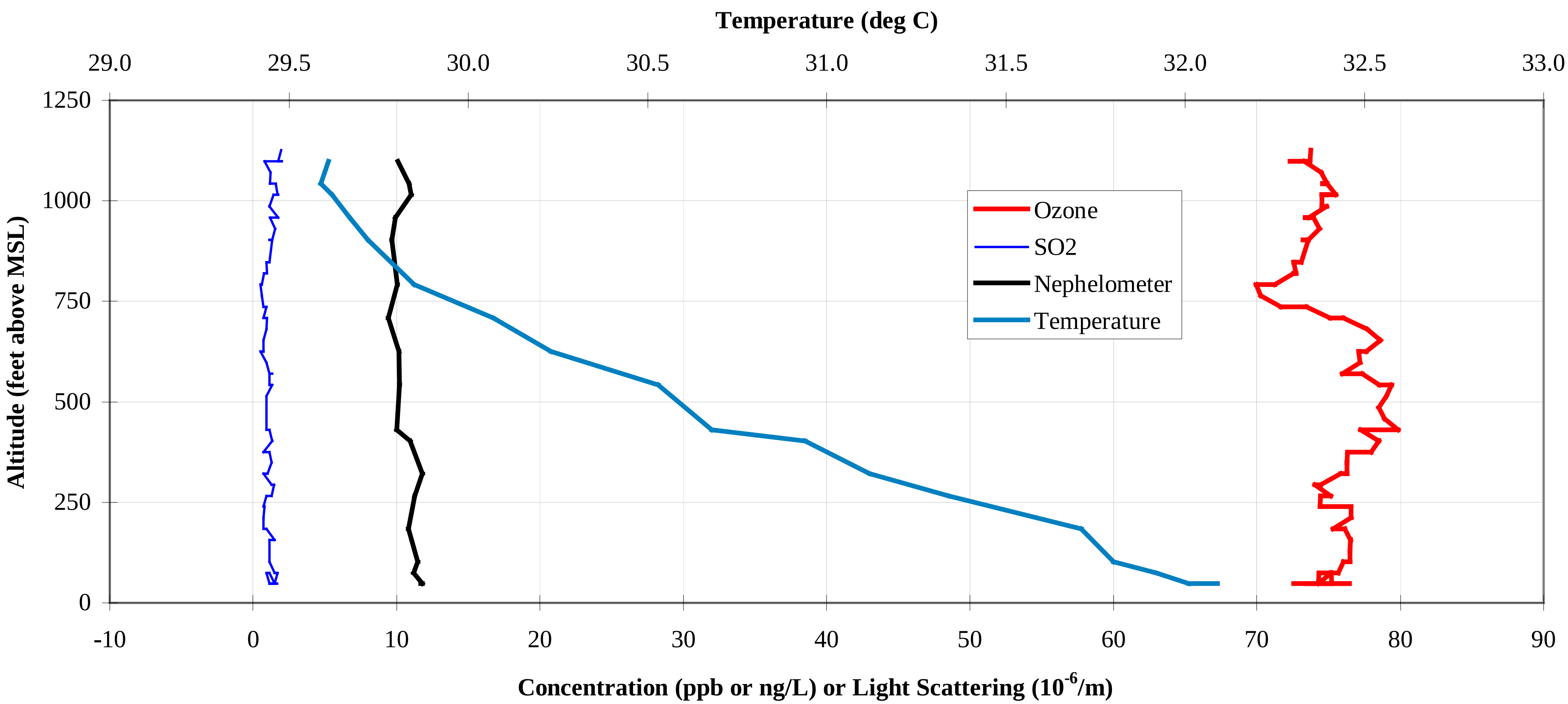


Figure 5-38. Vertical profile of air quality and temperature data collected over Houston, Texas, from 1336 to 1338 CST on August 25, 2000.

5.5 FLIGHT 141A AND 141B, AUGUST 26, 2000

On August 26, 2000, there was a morning and an afternoon flight. The morning flight consisted of a series of box climbs up to about 2000 ft msl (610 m msl) along with one box climb to 10,000 ft msl (3050 m msl) east of Texas City (**Figure 5-39**). When box climbs were not being flown, the flight altitude was maintained at about 1000 ft msl (305 m msl). The afternoon flight was to the southwest, south, and east of Houston with a single box climb over Galveston Bay to 6000 ft msl (1830 m msl) and several traverses at 1500 ft msl (457 m msl) over eastern Houston near the Ship Channel (**Figure 5-40**). When these box climbs and traverses were not being flown, the typical flight altitude was about 1000 ft msl (305 m msl). The flight path on this day was similar to the flight path on August 19, 2000.

5.5.1 Overview of Meteorology and Air Quality

A broad ridge of high pressure at 500 mb exsisted over the southern two-thirds of the United States (**Figure 5-41a**) with anticyclonic flow at 500 mb over Houston. This weather pattern provided a surface ridge over Texas/Louisiana and large scale flow from Florida to the Gulf of Mexico (**Figure 5-41b**). As shown in **Figure 5-42**, the mixing height as estimated by profiler reflectivity data (C_n^2) at Ellington Field was around 1640 ft msl (500 m msl) overnight and through 830 CST (1430 UTC). The mixing height then began to increase and by 1300 CST (1900 UTC) reached 7216 ft msl (2200 m msl). The box climb east of Texas City showed an inversion at 2800 ft msl (853 m msl) (**Figure 5-44**); the C_n^2 estimated mixing depth at that time was about 1640 ft msl (500 m msl).

The radar profiler wind data, the radar profiler wind runs, and the EDAS back-trajectories indicate recirculation of air from midnight to mid-morning below approximately 500 m. The recirculation was caused by southerly winds during the overnight hours followed by a few hours of land breeze (northerly flow), then a Bay Breeze (easterly flow at 1100 CST) in the afternoon (**Figure 5-43**). Above 2300 ft msl (700 m msl), both the radar profiler and EDAS back-trajectories show southeasterly flow around the high pressure system.

Peak ozone concentrations were observed in the Conroe vicinity north of Houston at 1700 CST (140 ppb at CAMS 65). In the Ship Channel area, only moderate ozone concentrations around 80 ppb occurred. North of the Ship Channel at CAMS 610, ozone concentrations were 119 ppb at 1100 CST. This ozone pattern is consistent with the radar profiler winds and back-trajectories as discussed above and is remarkably different from the previous day, which measured high ozone only in the central Houston and Ship Channel areas.

5.5.2 Characteristics of Ozone and NO_x

Morning Horizontal

- During the early morning hours, surface ozone concentrations were titrated at most sites, with concentrations ranging from near 0 to 30 ppb. Morning NO_x concentrations ranged from 60 to 100 ppb at CAMS 611 (near Baytown) and CAMS 603 (near the Ship Channel) to near zero at outlying sites such as CAMS 34 (Galveston).

Morning Vertical

- As shown in **Figure 5-44**, aloft peak ozone concentrations were only 55 ppb (above 5000 ft msl) and were at too high an altitude to be drawn into the growing mixed layer over Houston during the day. However, the layer between 2000 and 5000 ft msl (610 to 1524 m msl) would be mixed down, but the layer generally contained ozone concentrations of 30 to 40 ppb.
- The La Porte box climb (**Figure 5-45**) near the Ship Channel showed a shallow inversion at 350 ft msl (107 m msl) that confined ground-based pollutants to this shallow layer.
  - Beneath the inversion, ozone concentrations were around 5 to 28 ppb, and there was a layer of NO_y (20 ppb at 200 ft msl or 60 m msl) and NO (5 ppb at 150 ft msl or 46 m msl). Collocated SO_2 concentrations were 0 ppb.
  - Above the inversion, NO_y and NO concentrations decreased and ozone concentrations increased to about 30 ppb.
- In the descending profile for the La Porte box climb, two layers of pollutants were observed. NO_y and NO concentrations of 35 and 5 ppb, respectively, were observed at around 1400 ft msl (427 m msl). At 1800 ft msl (550 m msl), a layer of NO_y and NO concentrations of 65 and 23 ppb, respectively, were observed. In both layers, ozone concentrations were titrated to 5 to 10 ppb.

Afternoon Horizontal

- As discussed above, surface ozone concentrations peaked on the east side of Houston at around 1100 CST and on the north side of Houston at around 1500 CST, which is consistent with the wind pattern; onshore flow developed around 1100 CST, which transported ozone to the north.
- A series of traverses over the region north of the Ship Channel showed ozone concentrations of 100 to 110 ppb at 1145 CST at an elevation of about 1500 ft msl (457 m msl) (**Figure 5-46**). Note that where ozone concentrations are shown dropping to zero, calibrations were being performed and during these periods, all data should be ignored for this analysis. Concentrations of NO_y (as high as 20 ppb) and SO_2 (5 ppb) were also observed within this time frame. A second traverse at 1340 CST over the Ship Channel region at 1500 ft msl (457 m msl) showed similar concentrations. Here ozone concentrations were as high as 117 ppb, NO_y, NO, and SO_2 concentrations were 20 ppb, 0 to 2 ppb, and 10 ppb, respectively.

Afternoon Vertical

- The Galveston Bay box climb starting at 1120 CST shows that air below about 1800 ft msl (548 m msl) is relatively clean (**Figure 5-47**). The thickness of this layer is consistent with the thickness of the Bay Breeze. Ozone concentrations were approximately 30 to 40 ppb, while NO_y, NO, and SO_2 concentrations were 0 to 2, 0, and 0 to 2 ppb, respectively.
- Between 1800 and 2500 ft msl (548 and 762 m msl) ozone and NO_y concentrations increased to about 45 to 50 ppb and 3 ppb, respectively. Between 2500 and 4000 ft msl (762 and 1219 m msl) ozone and NO_y concentrations decreased to about 30 to 40 ppb and 0 to 2 ppb, respectively. A calibration occurred above 4000 ft msl.

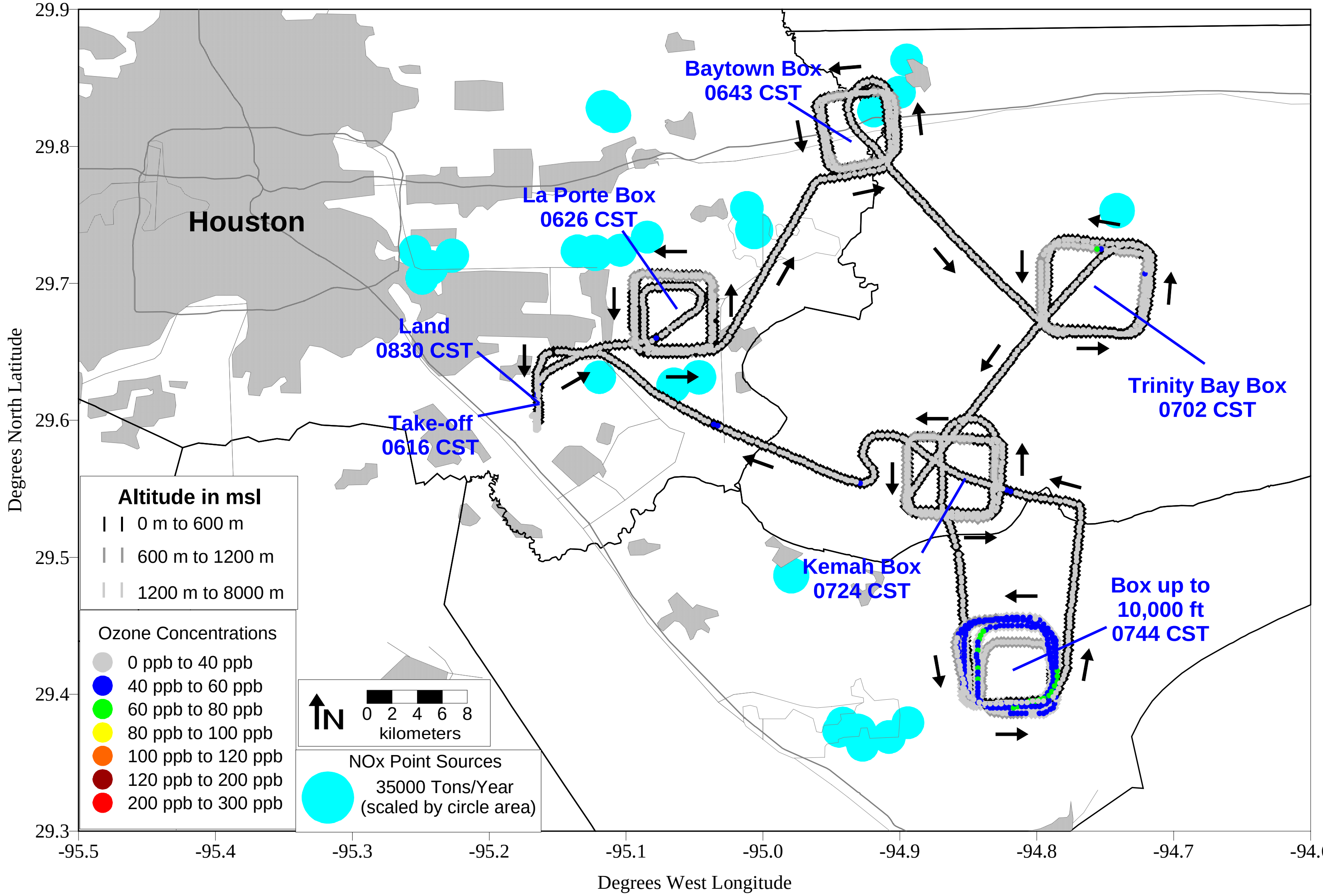


Figure 5-39. Flight 141 flight position, altitude, and aloft ozone concentrations on the morning of August 26, 2000.

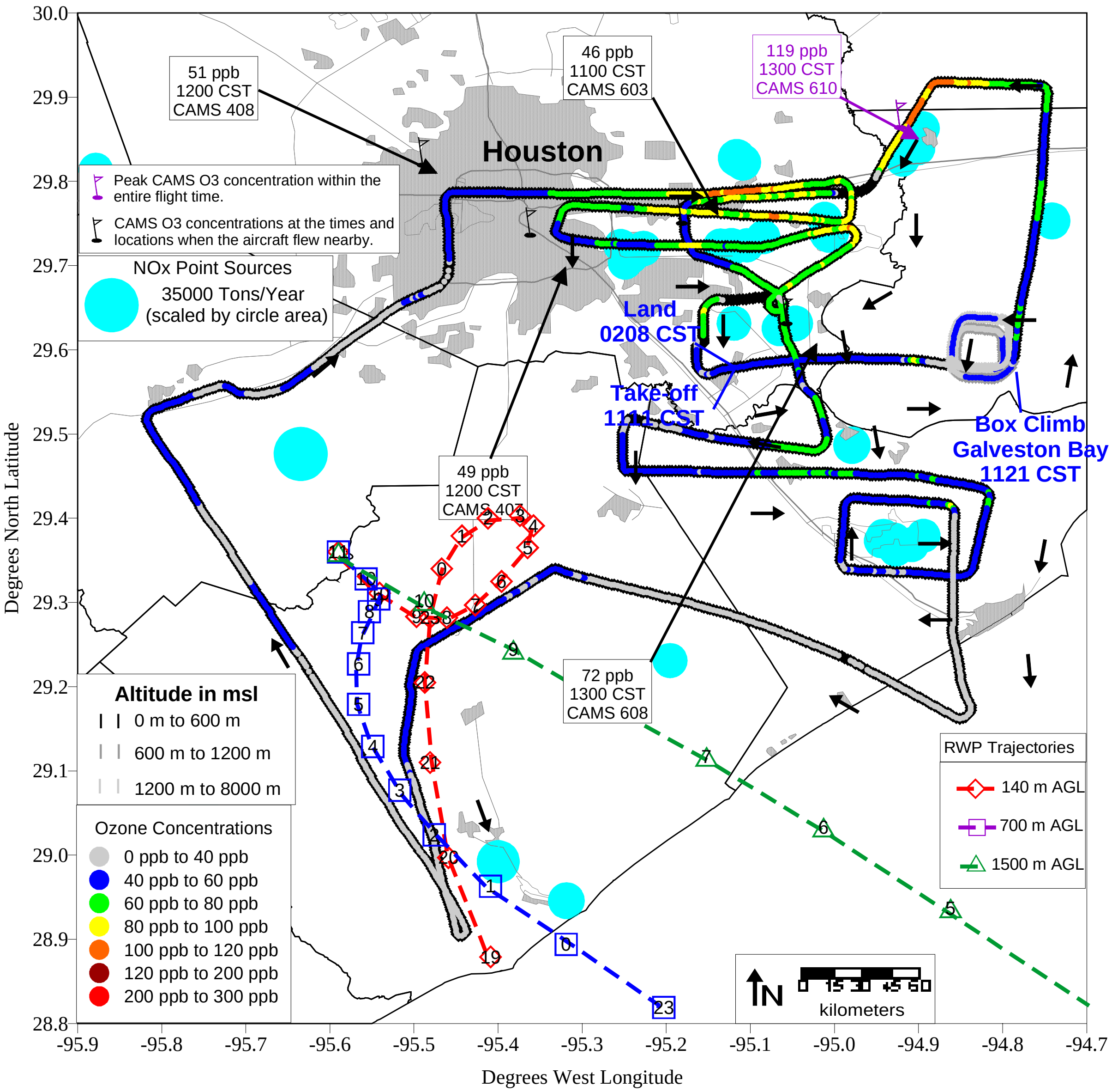


Figure 5-40. Flight 141 flight position, altitude, aloft ozone concentrations, and CAMS surface ozone concentrations on the afternoon of August 26, 2000.

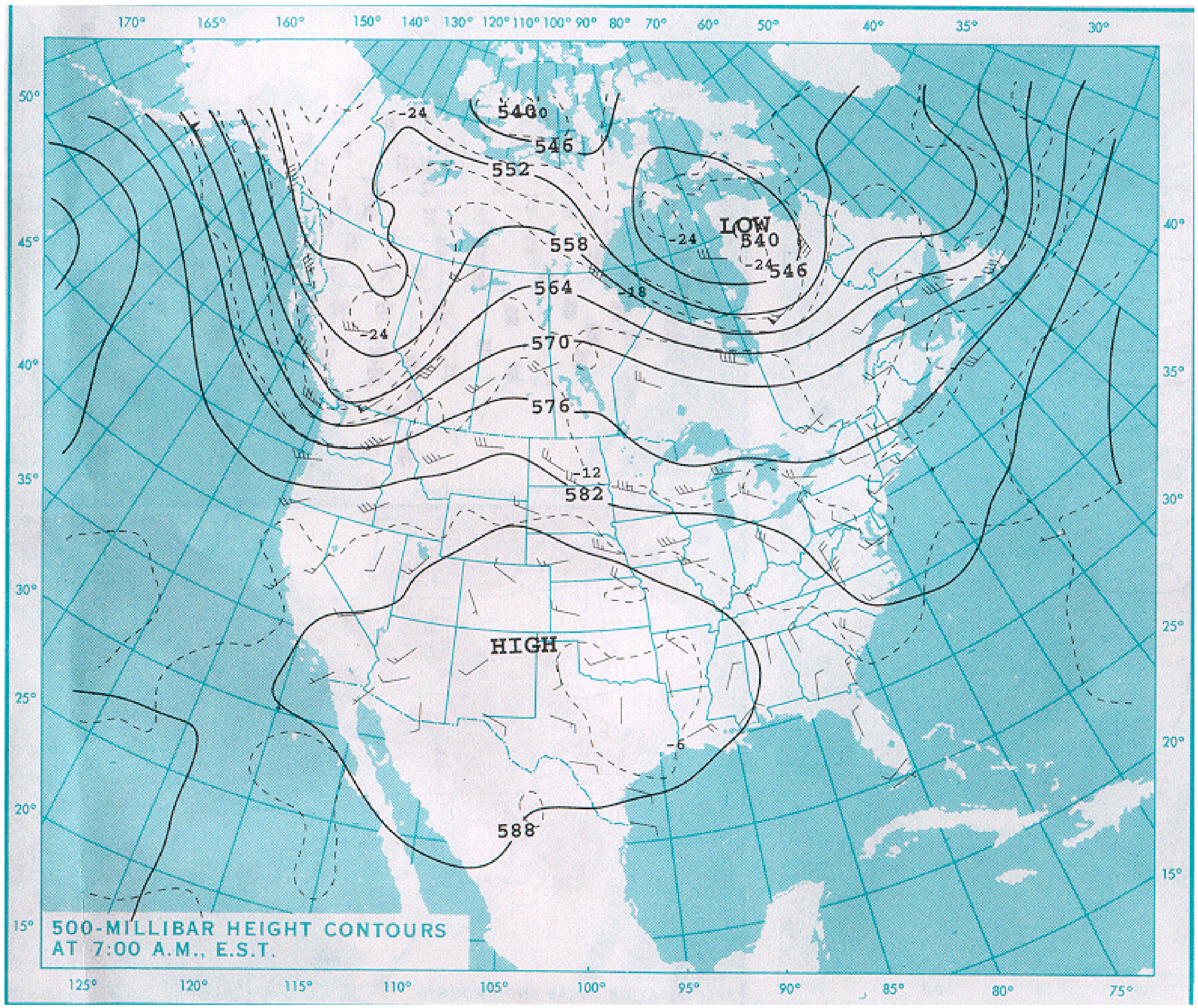


Figure 5-41a. Height contours of the 500-mb pressure surface at 0600 CST on August 26, 2000.

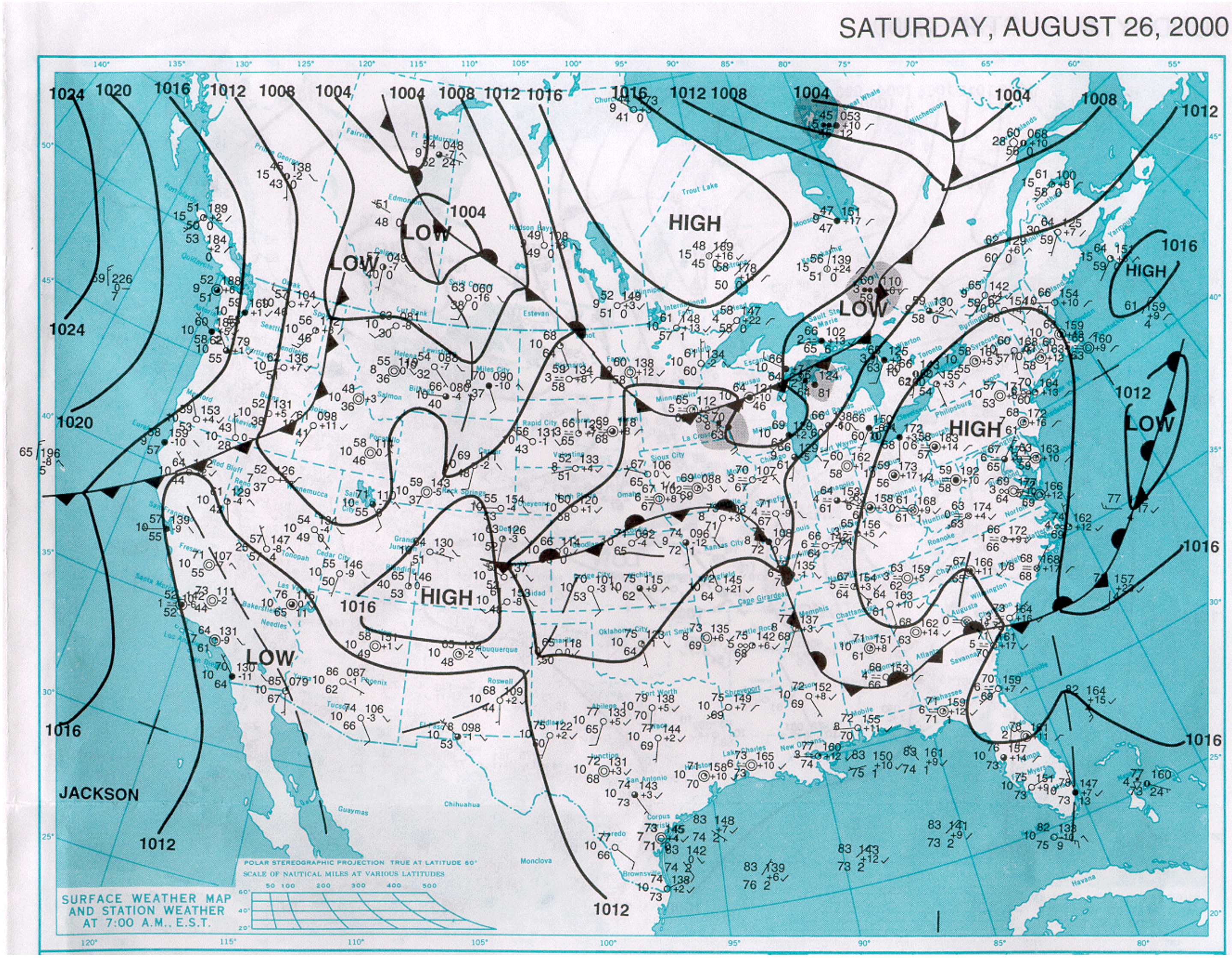


Figure 5-41b. Surface analysis at 0600 CST on August 26, 2000.

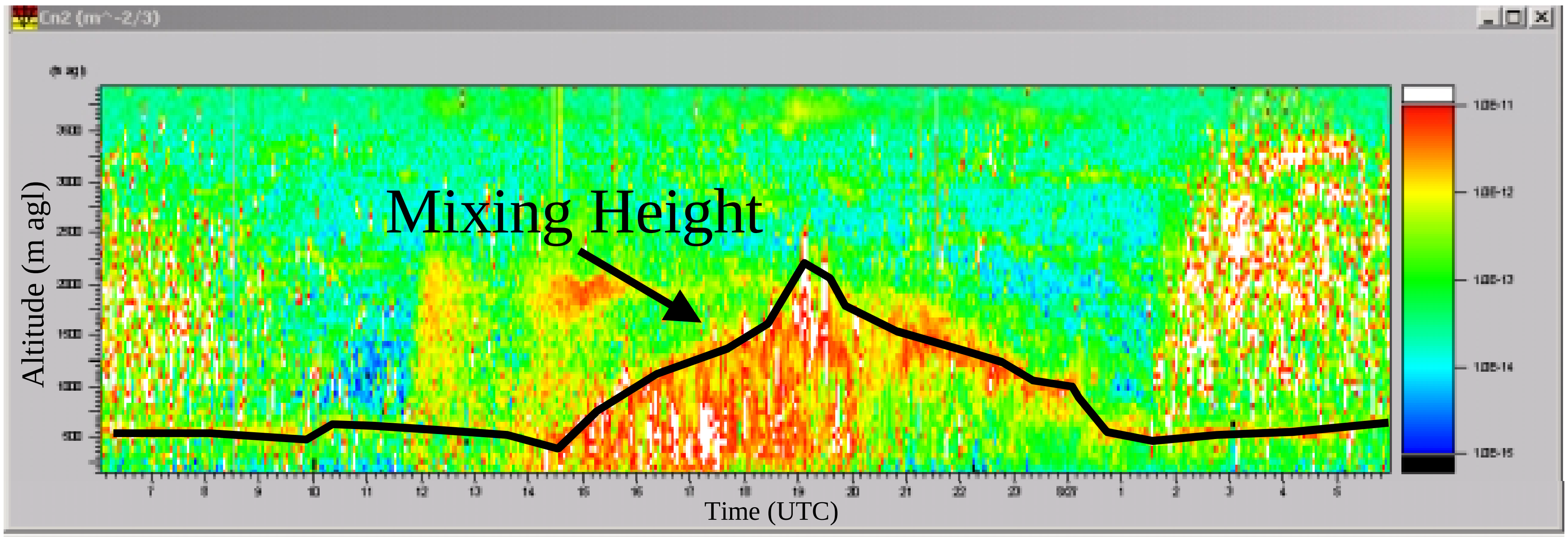


Figure 5-42. Radar wind profiler reflectivity data (C_n^2) and estimated mixing height for August 26, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

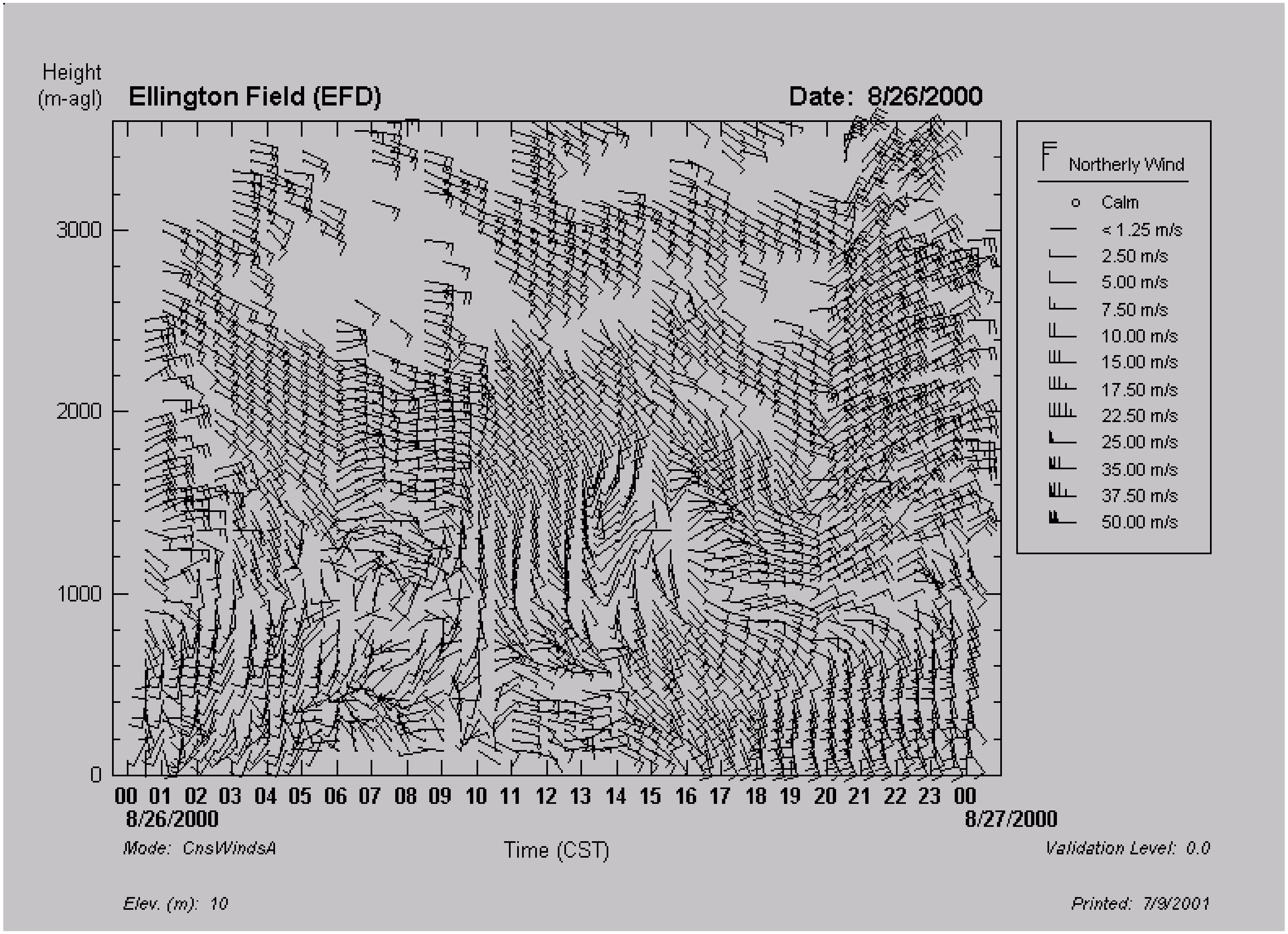


Figure 5-43. Radar wind profiler data for August 26, 2000 at Ellington Field, Houston. Note that the profiler is 10 m above msl.

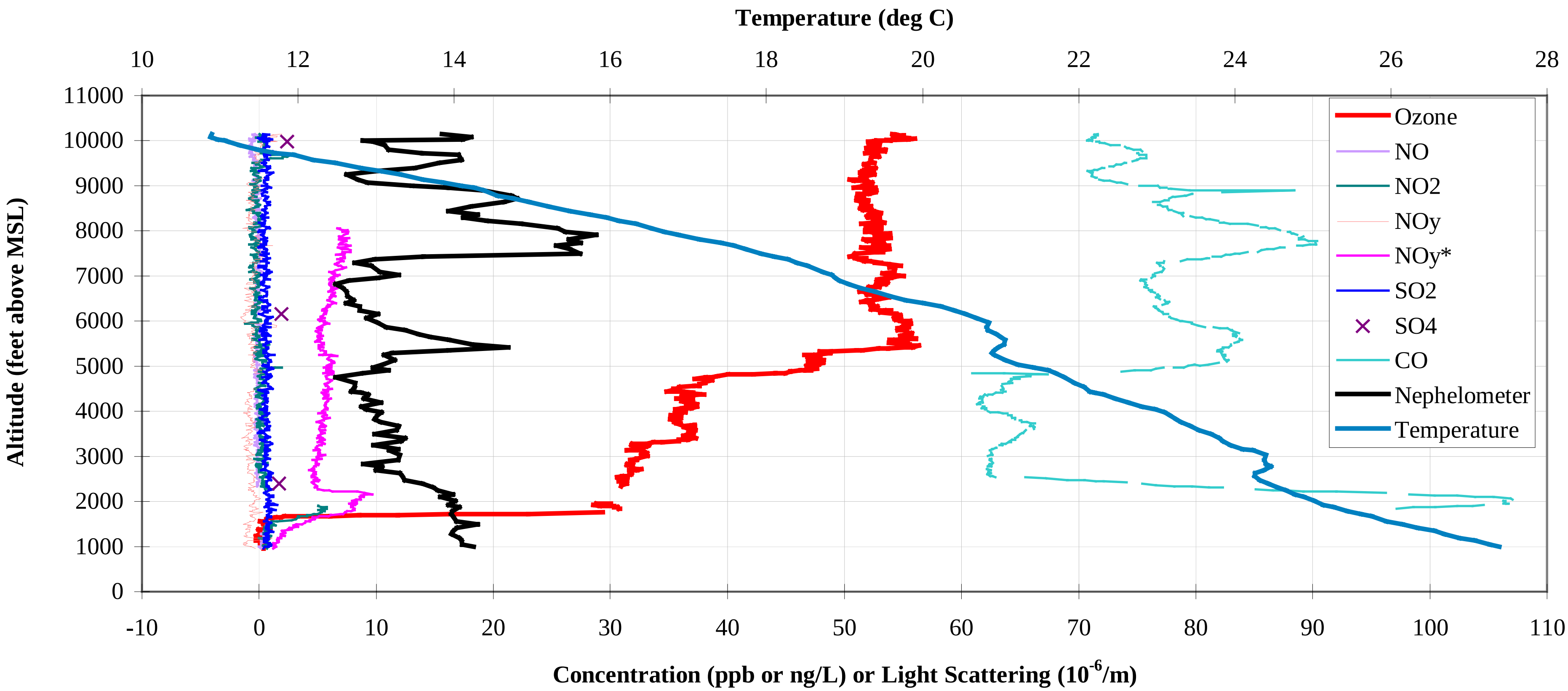


Figure 5-44. Vertical profile of air quality and temperature data collected over Galveston Bay (east of Texas City) from 0804 to 0815 CST on August 26, 2000.

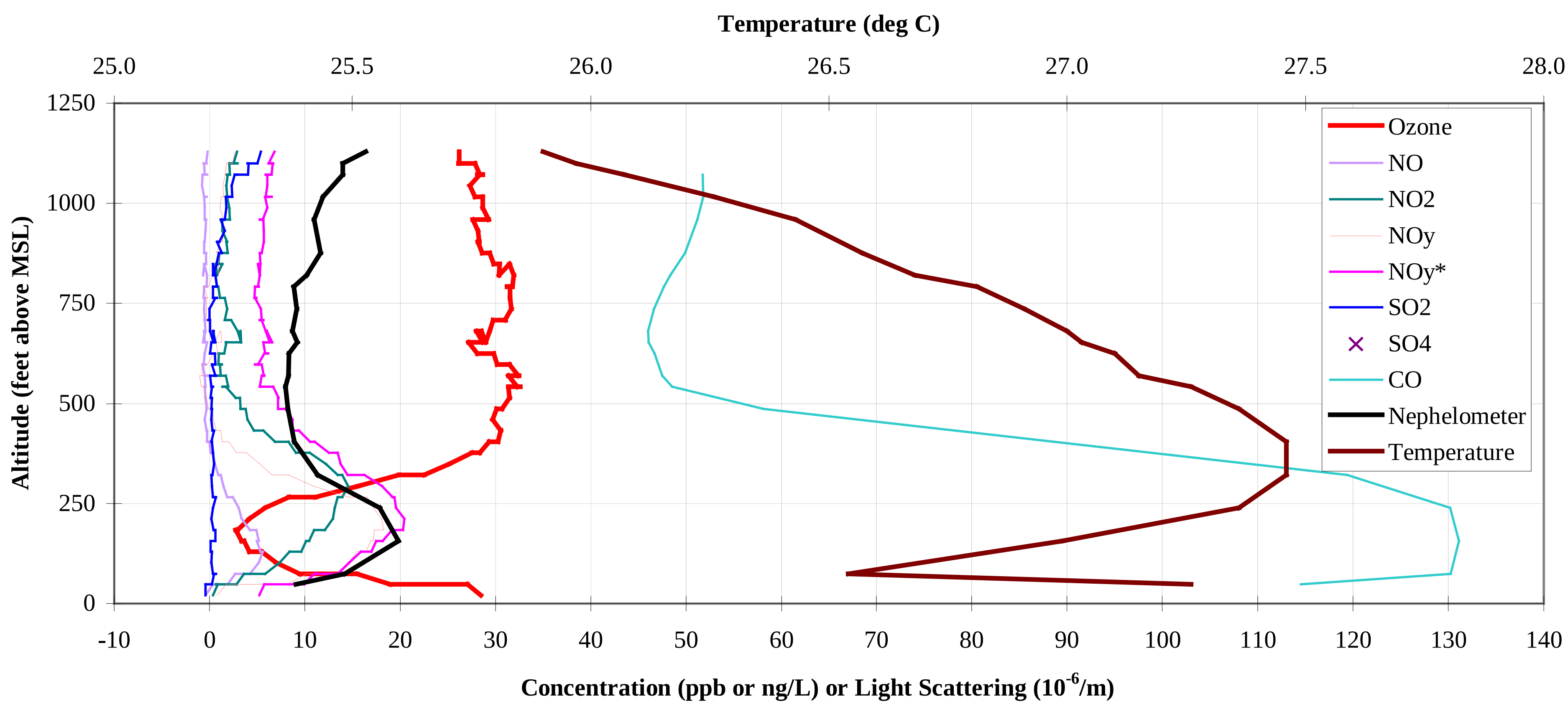


Figure 5-45. Vertical profile of air quality and temperature data collected over La Porte, Texas from 0624 to 0627 CST on August 26, 2000.

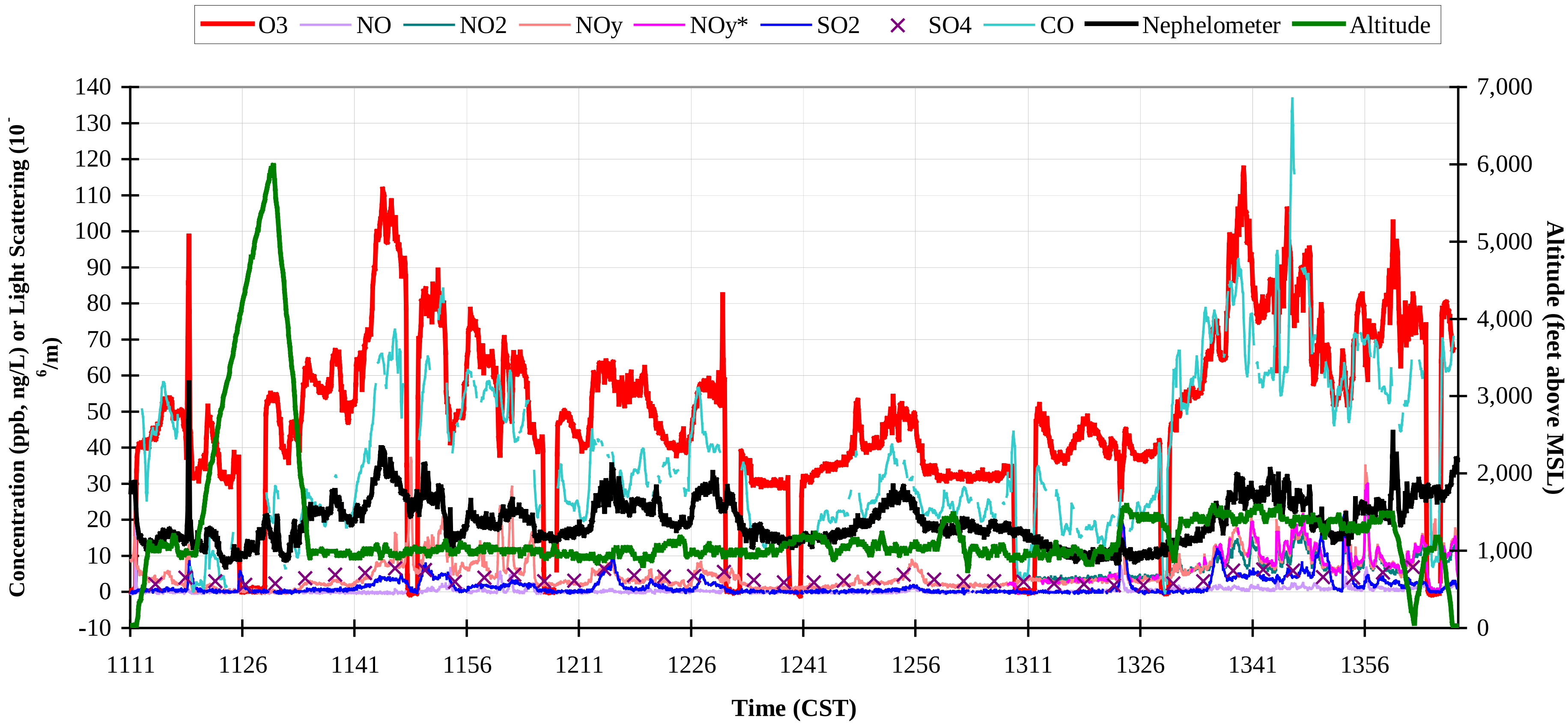


Figure 5-46. Time-series plot of air quality and temperature data collected from 1111 to 1408 CST on August 26, 2000.

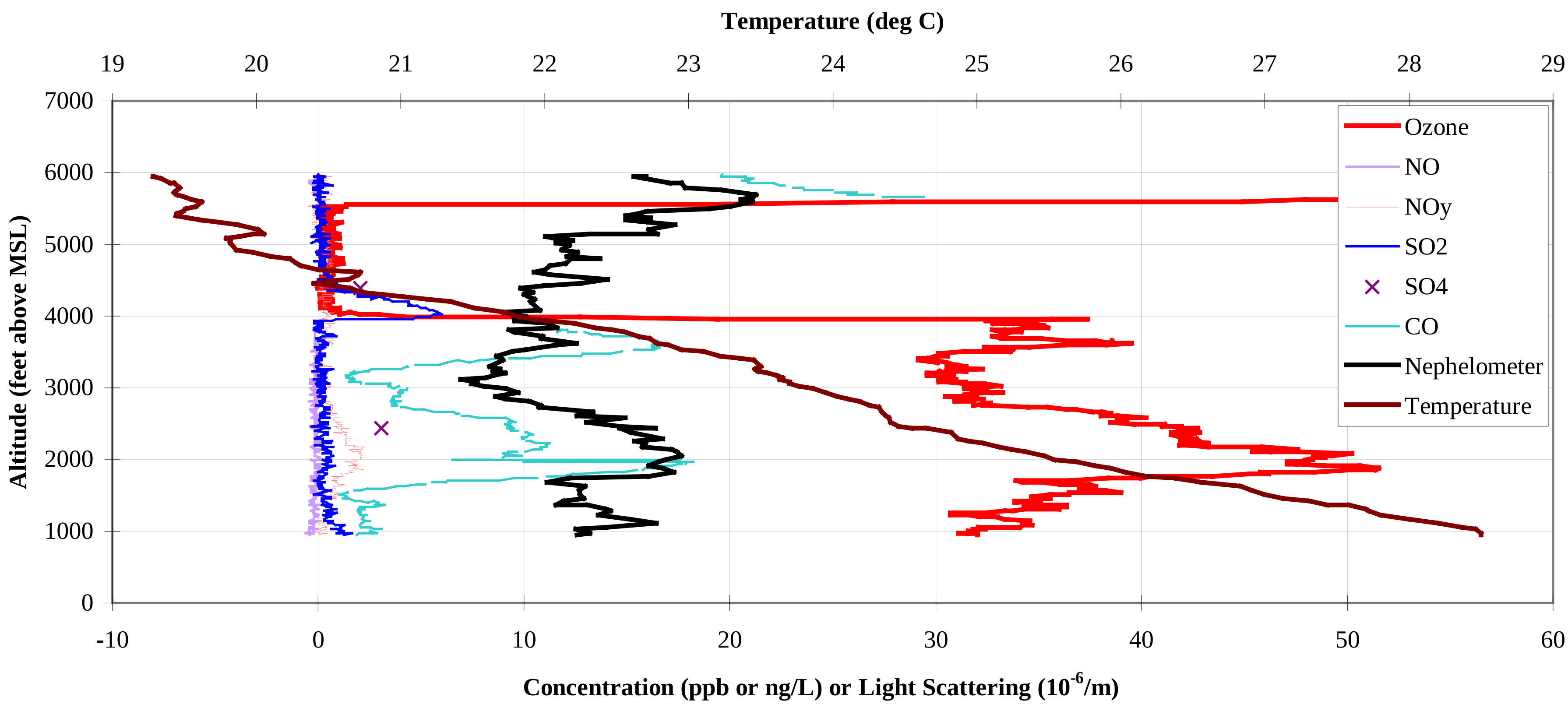


Figure 5-47. Vertical profile of air quality and temperature data collected over Galveston Bay, Texas from 1120 to 1131 CST on August 26, 2000.

5.6 FLIGHT 143A AND 143B, AUGUST 29, 2000

On August 29, 2000, there was a morning and a late morning/afternoon flight. The morning flight consisted of a series of box climbs up to about 2000 ft msl (610 m msl) along with one box climb to 10,000 ft msl (3050 m msl) east of Texas City (**Figure 5-48**). When box climbs were not being flown, the flight altitude was maintained at about 1000 ft msl (305 m msl). The late morning/afternoon flight was flown to the southwest, south, and east of Houston with a single box climb over Galveston Bay to 6000 ft msl (1830 m msl) and several traverses at 1500 ft msl or (457 m msl) over eastern Houston near the Ship Channel (**Figure 5-49**).

5.6.1 Overview of Meteorology and Air Quality

There was a broad ridge of high pressure at 500 mb over the southern two-thirds of the United States (**Figure 5-50a**) with anticyclonic flow over eastern Texas. High pressure at the surface was centered over Lake Charles, Louisiana, extending over Houston (**Figure 5-50b**). Radar profiler reflectivity (C_n^2) data were not available for this day to estimate mixing heights and radar profiler wind data were not available prior to 0800 CST.

The radar profiler wind data (**Figure 5-51**) and back-trajectories (Figure 5-49) indicate a same-day recirculation of air below about 3280 ft msl (1000 m msl). The recirculation in the lower levels was light westerly in the morning followed by a few hours of light and variable flow, and then an easterly Bay Breeze at 1400 CST followed by a southwesterly Gulf Breeze at 1500 CST and for the remainder of the afternoon. Above 3280 ft msl (1000 m msl) the radar profiler back-trajectories and wind data show southerly flow in the morning and northeasterly flow in the afternoon. Visible satellite imagery (**Figure 5-52**) showed the anticyclonic circulation around the surface high-pressure system, with a land breeze east of Galveston Bay and a Gulf Breeze west of the bay.

The recirculation in the lowest 3280 ft msl (1000 m msl) allowed for high ozone concentrations north of the Houston Ship Channel as observed at surface CAMS sites and by the aircraft. The highest surface ozone concentration was 145 ppb at CAMS 610 at 1500 CST near Baytown and six CAMS sites (all north of the Ship Channel) reported ozone concentrations of at least 100 ppb.

5.6.2 Characteristics of Ozone and NO_x

Morning Horizontal

- During the early morning hours, surface ozone concentrations were titrated at all CAMS sites in the Houston area, with concentrations ranging from about 0 ppb to 20 ppb. Morning NO_x concentrations ranged from 160 ppb at CAMS 603 (near the Ship Channel) to around 30 ppb at outlying sites such as CAMS 26 (northwest of Houston).
- As shown in **Figure 5-53**, aloft ozone concentrations observed during a morning box climb east of Texas City above 2000 ft msl (610 m msl) and below 4500 ft msl (1372 m msl) ranged from about 30 to 55 ppb. The 24-hr EDAS back-trajectories indicated that the air at these levels came off the Gulf of Mexico overnight (**Figure 5-54**).

Morning Vertical

- The La Porte box climb **(Figures 5-55a and 5-55b)** showed a nighttime inversion at 500 ft msl (152 m msl) and a second temperature inversion at about 1900 ft msl (580 m msl).
  - Beneath the lower inversion, there was a layer of NO_y and NO concentrations at about 400 ft msl (122 m msl) with peak concentrations of 125 and 90 ppb, respectively. Collocated ozone concentrations were titrated to 5 to 10 ppb. There was no SO_2 in this layer.
  - Above the first inversion and below about 1500 ft msl (457 m msl), NO_y and NO concentrations decreased and ozone concentrations increased to about 30 ppb.
  - Just below the second inversion, there was a layer of NO_y (15 ppb at 1700 ft msl or 520 m msl) and NO (2 to 3 ppb at 1700 ft msl or 520 m msl) with low ozone concentrations (15 ppb at 1700 ft msl or 520 m msl). Again, SO_2 concentrations were 0 ppb.
  - Above the second inversion, NO_y and NO concentrations decreased and ozone concentrations increased to about 35 ppb.

Late Morning/Afternoon Horizontal

- The midday stagnation and light southerly winds allowed ozone concentrations to increase just north of the Ship Channel, then the afternoon Gulf Breeze transported ozone to the north of Houston. The highest surface ozone concentration was 145 ppb at CAMS 610 at 1500 CST near Baytown, and six CAMS sites (north of the Ship Channel) reported ozone concentrations of at least 100 ppb. CAMS 65 in Conroe, well north of Houston, peaked at 135 ppb at 1800 CST. CAMS stations west and south of the Ship Channel reported ozone concentrations of under 80 ppb. In general, the sites nearest the Ship Channel had peak ozone concentrations around 1400 CST, while sites north of the Ship Channel had peak ozone concentrations at 1500 CST.
- The highest ozone concentration observed by the aircraft was 180 ppb at 1340 CST at 1500 ft msl (457 m msl) just north of the Ship Channel (Figure 5-49 and **Figure 5-56**). This peak coincided with local NO_y and SO_2 concentration peaks of 25 ppb and 10 to 20 ppb, respectively. Other high ozone peaks between 1330 and 1353 CST were also associated with SO_2.

Late Morning/Afternoon Vertical

- The only box climb during the late morning/afternoon flight at 1114 CST shows that ozone concentrations over Galveston Bay ranged from 40 to 70 ppb, and NO_y, NO, and SO_2 concentrations were 0 to 10 ppb, 0 to 1 ppb, and 0 ppb, respectively (**Figure 5-57**).
  - Between 1000 ft msl (305 m msl) (the start of the box climb) and 2200 ft msl (671 m msl), ozone, NO_y, and NO concentrations were 55 to 60 ppb, 5 to 10 ppb, and 1 to 2 ppb, respectively. The radar profiler winds (Figure 5-51) within this layer were light westerly indicating transport of relatively clean air from southern Houston.
  - From 2200 ft msl (671 m msl) to around 3500 ft msl (1067 m msl), ozone, NO_y, and NO concentrations were 40 to 45 ppb, 10 ppb, and 0 ppb, respectively. The radar

profiler winds within this layer were westerly at around 2.5 m/s indicating transport from southern Houston.

– A small temperature inversion was observed at 3600 ft msl (1097 m msl), above which ozone concentrations rose to 50 to 60 ppb up to 4500 ft msl (1372 m msl). NO_y concentrations were 0 ppb in this layer. The radar profiler winds were westerly at 2.5 m/s within this layer, again indicating that air originating over southern Houston had moved over Galveston Bay.

– A stronger temperature inversion was observed at 4500 ft msl (1372 m msl), above which ozone concentrations increased to 60 to 70 ppb, which is 10 to 15 ppb higher than the early morning aloft concentrations. NO_y and NO concentrations were 0 ppb above 4500 ft msl (1372 m msl).

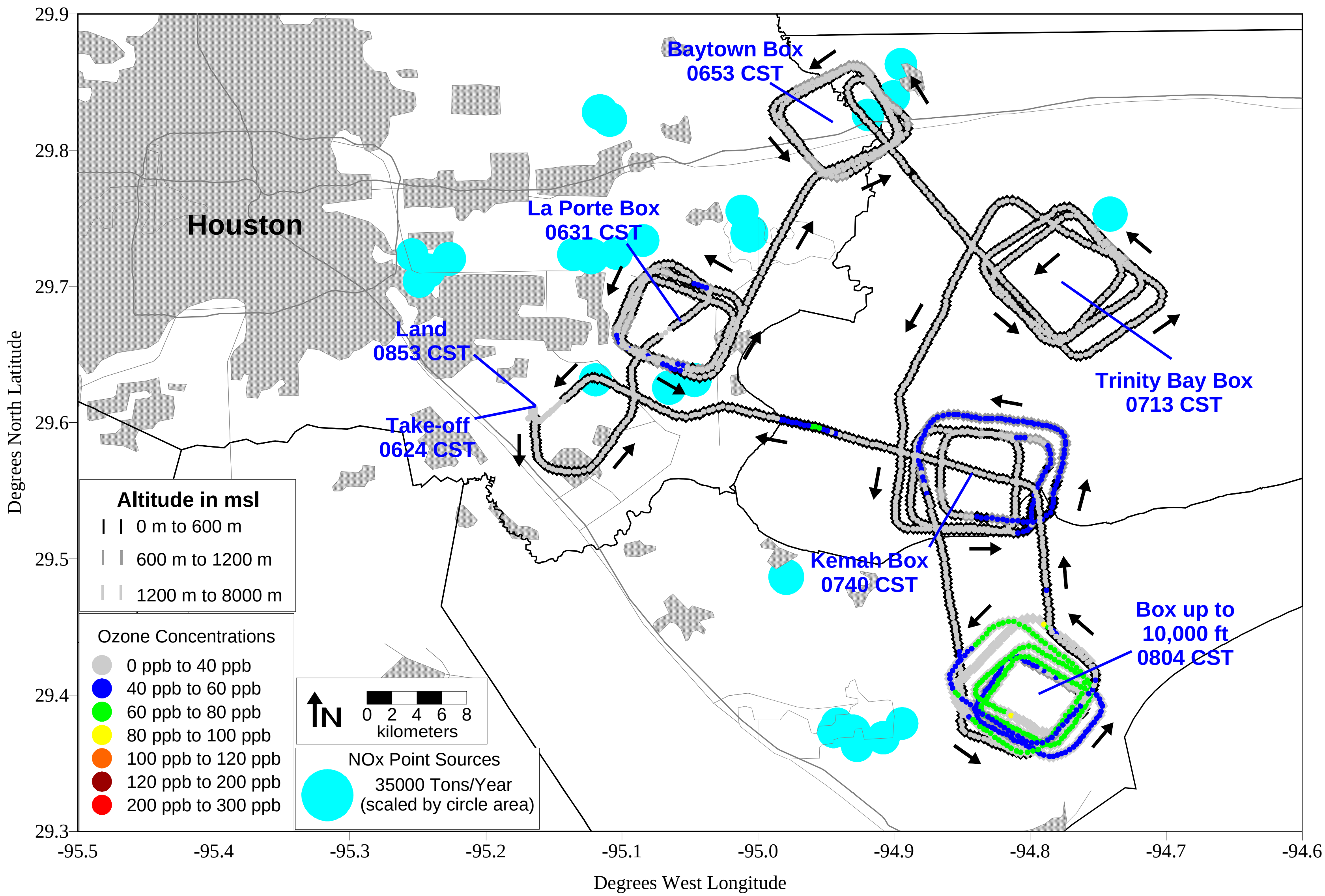


Figure 5-48. Flight 143 flight position, altitude, and aloft ozone concentrations on the morning of August 29, 2000.

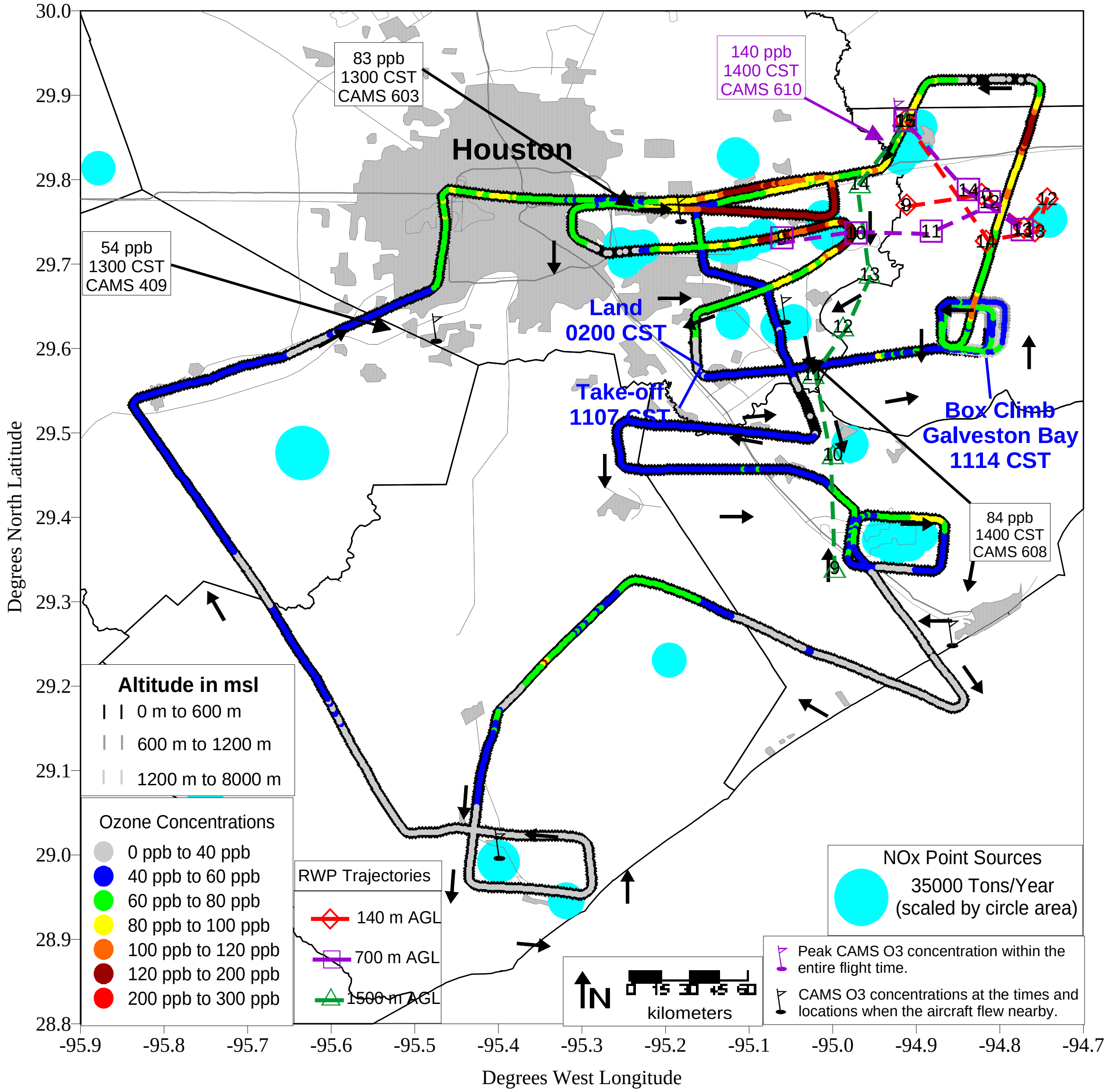


Figure 5-49. Flight 143 flight position, altitude, aloft ozone concentrations, and CAMS surface ozone concentrations on the afternoon of August 29, 2000.

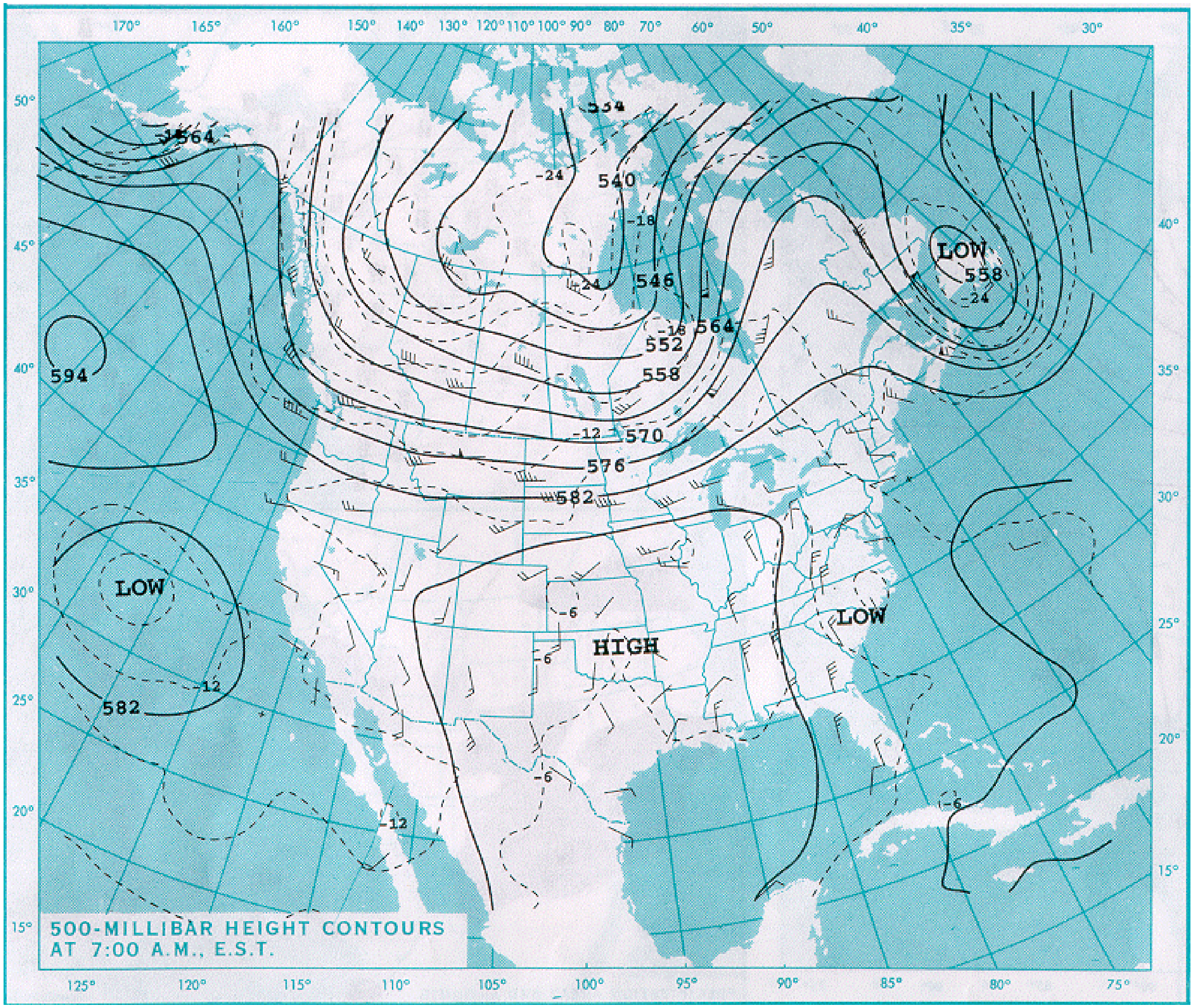


Figure 5-50a. Height contours of the 500-mb pressure surface at 0600 CST on August 29, 2000.

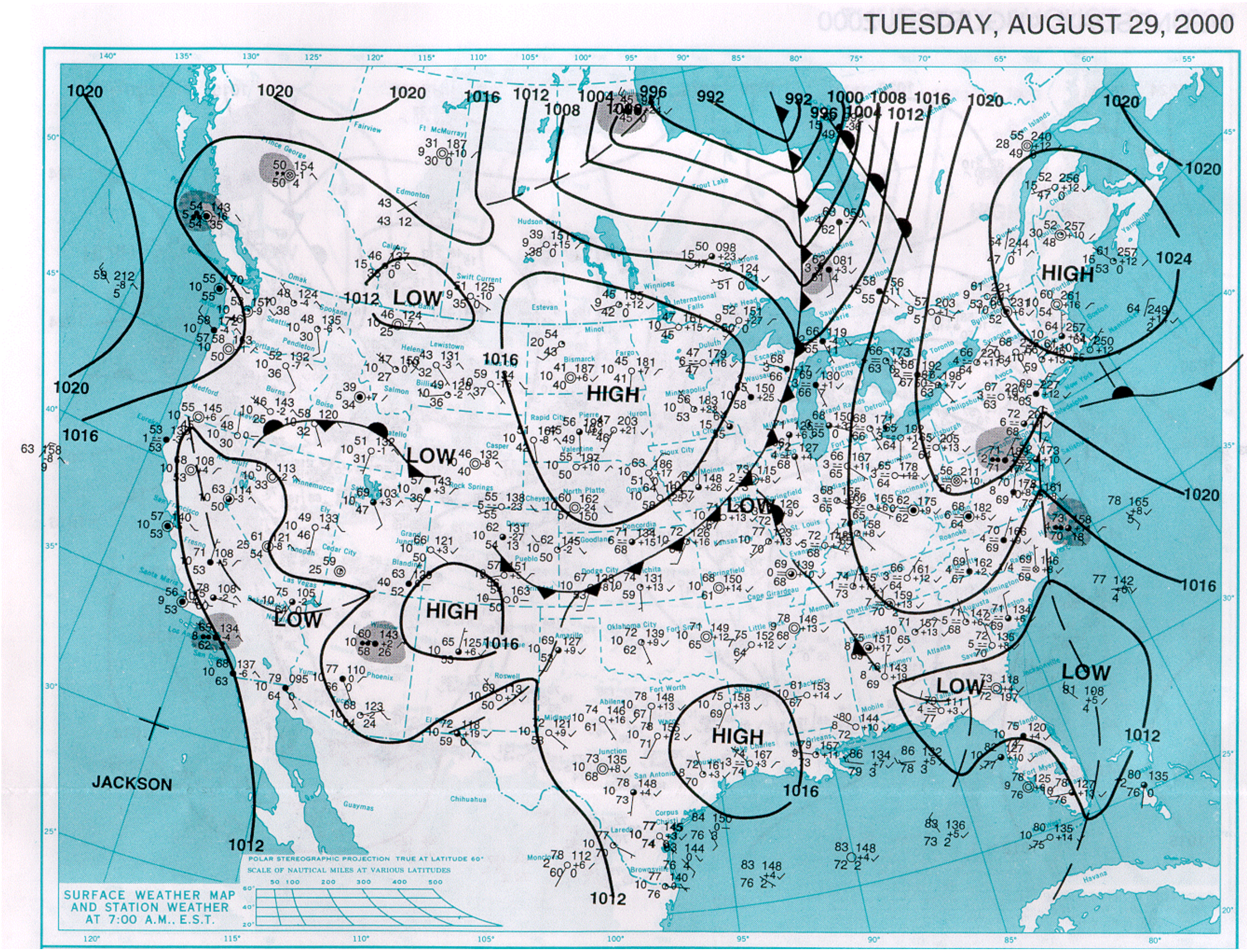


Figure 5-50b.   Surface analysis at 0600 CST on August 29, 2000.

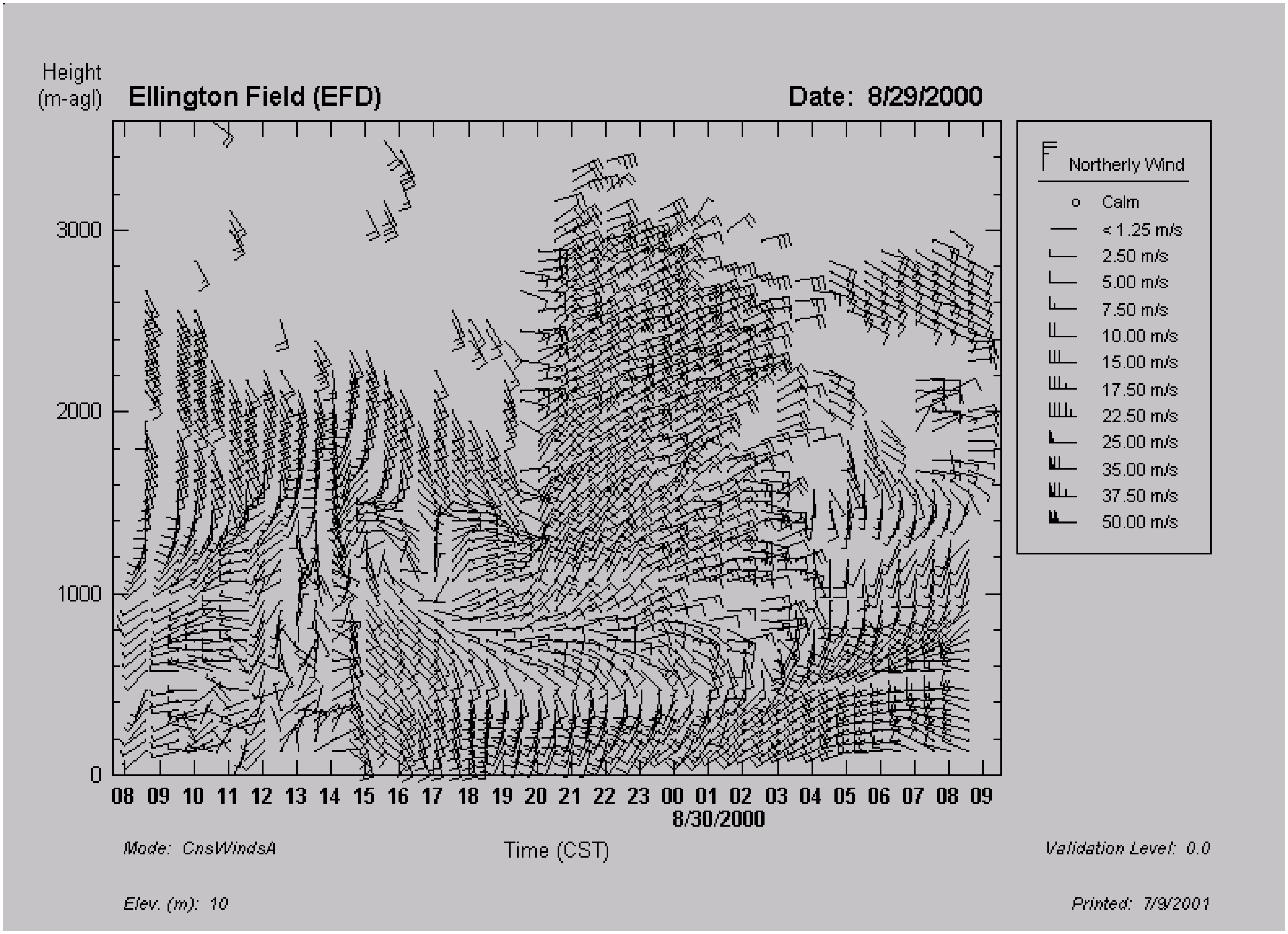


Figure 5-51. Radar wind profiler data for August 29, 2000 at Ellington Field, Houston. Note that the profiler is 10 m above msl.

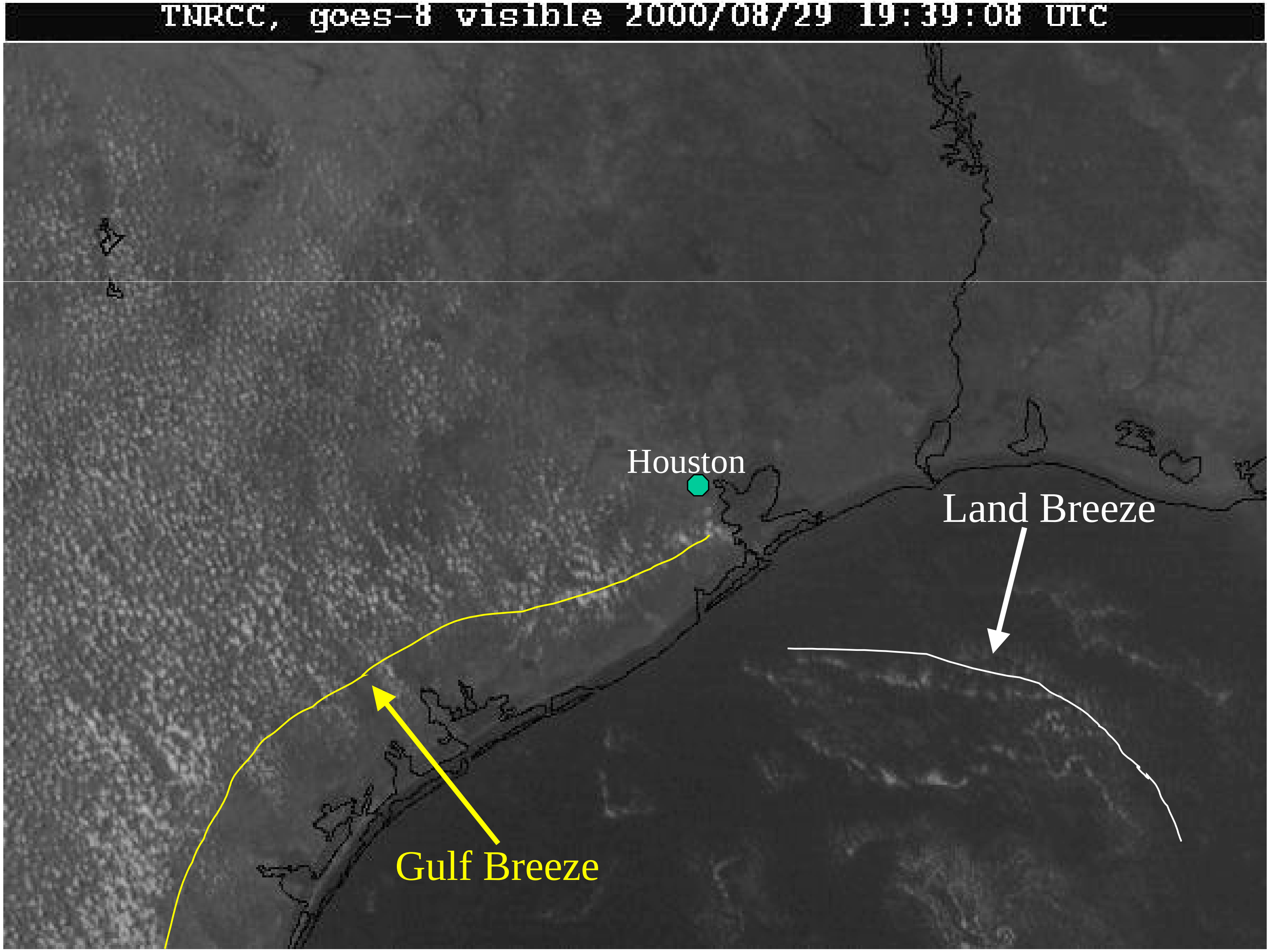


Figure 5-52. Visible satellite imagery at 1339 CST (1939 UTC) on August 29, 2000.

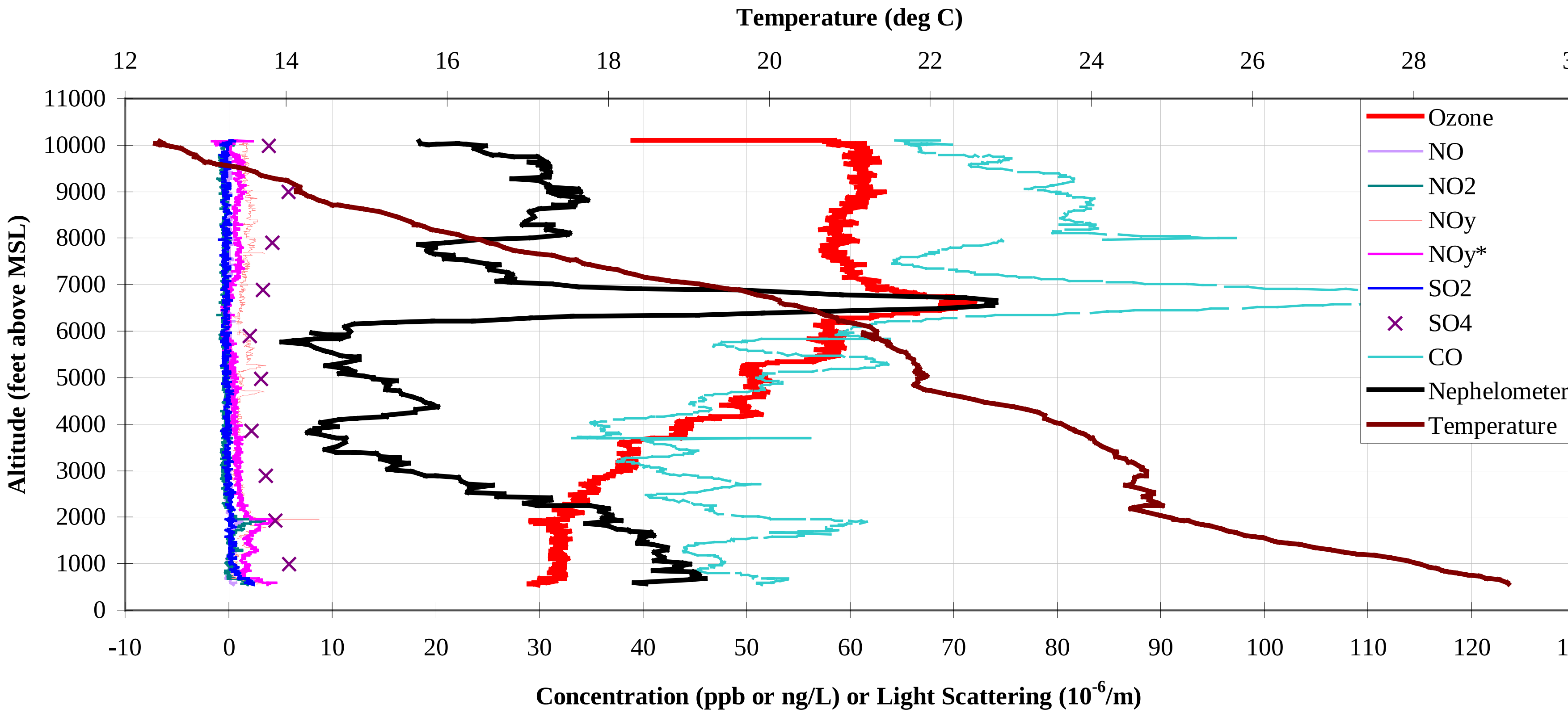


Figure 5-53. Vertical profile of air quality and temperature data collected over Galveston Bay (east of Texas City) from 0805 to 0826 CST on August 29, 2000.

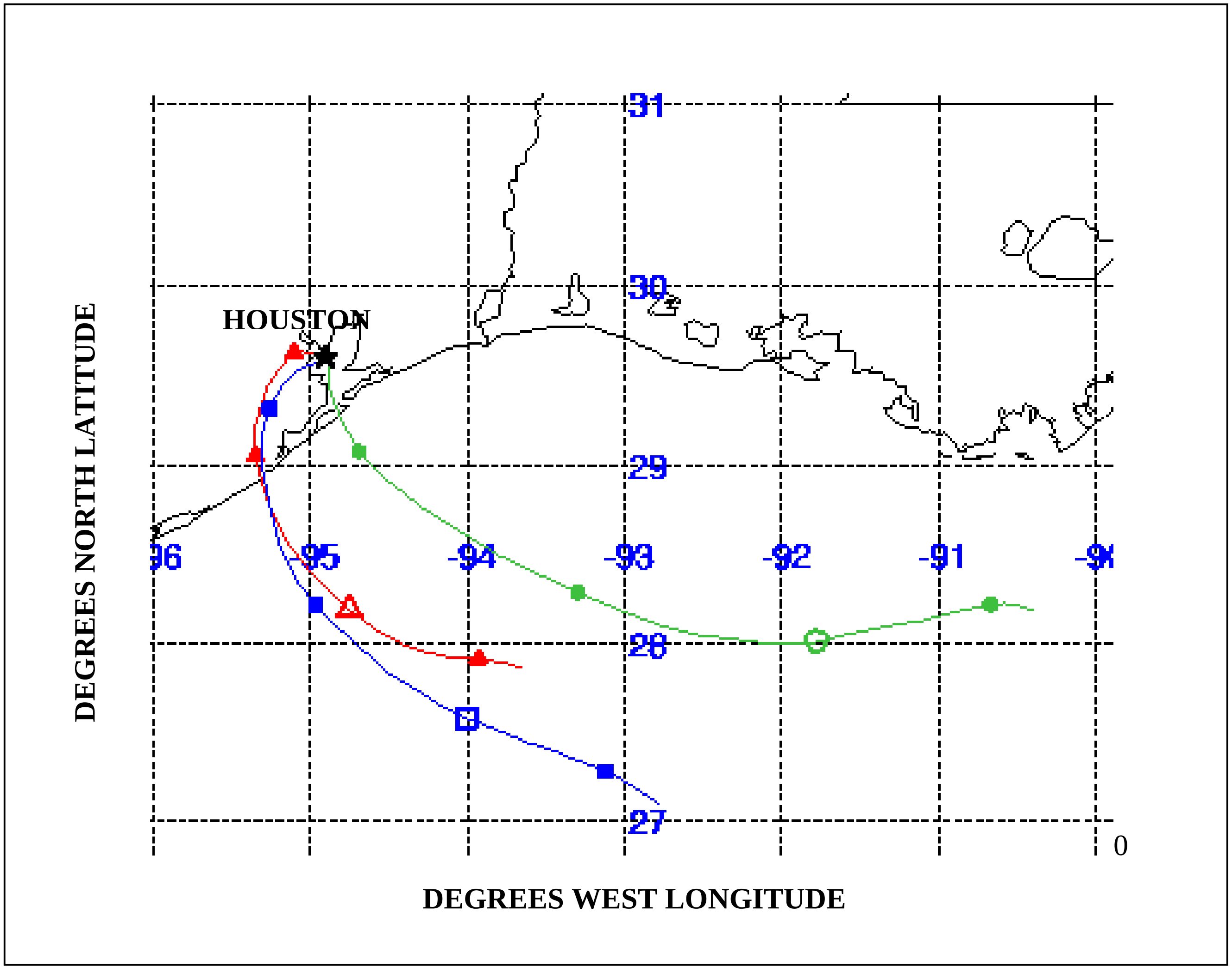


Figure 5-54. Twenty-four-hour back-trajectories for 140 m agl (red line), 700 m agl (blue line), and 1500 m agl (green line) from the general flight area in Houston on August 29, 2000, at 0900 CST.

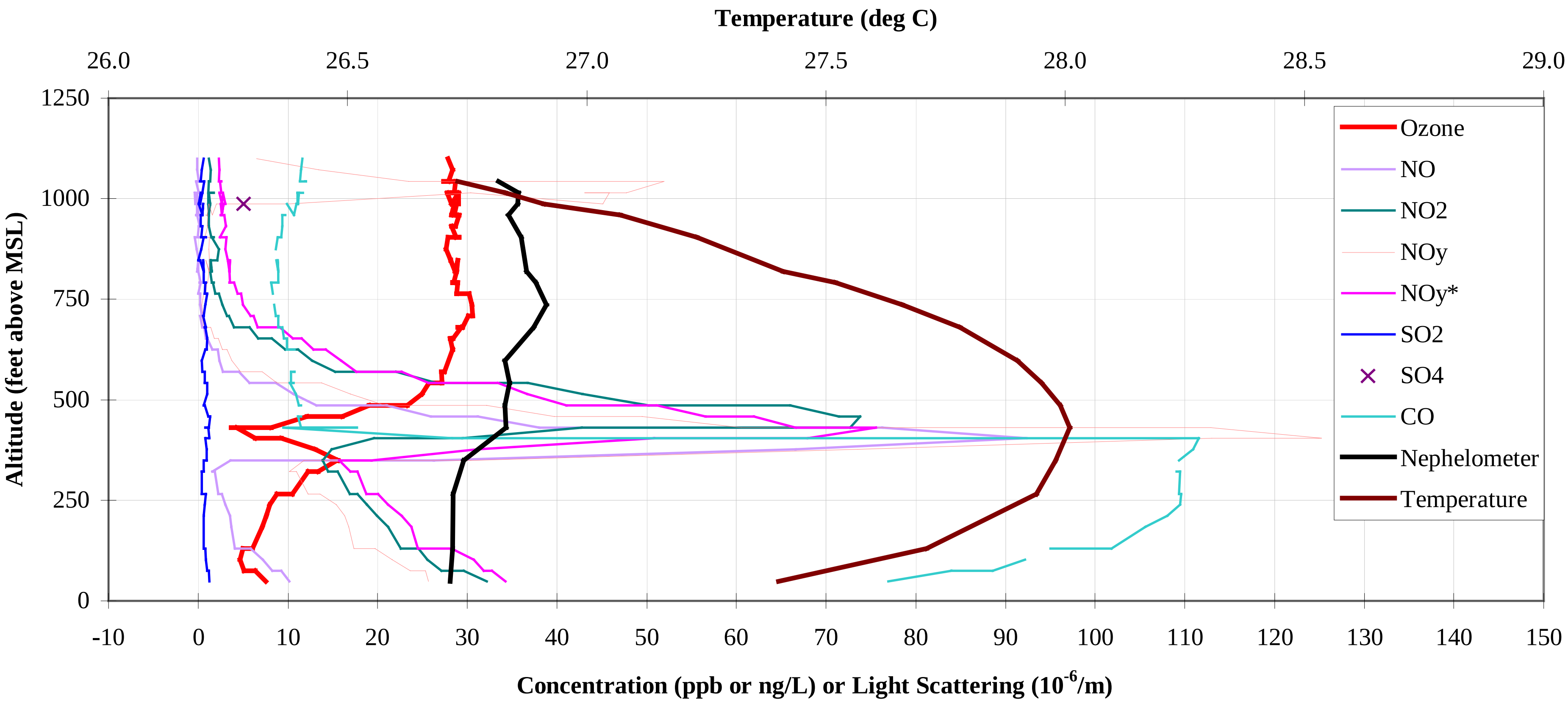


Figure 5-55a. Vertical profile of air quality and temperature data collected over La Porte, Texas, from 0629 to 0632 CST on August 29, 2000.

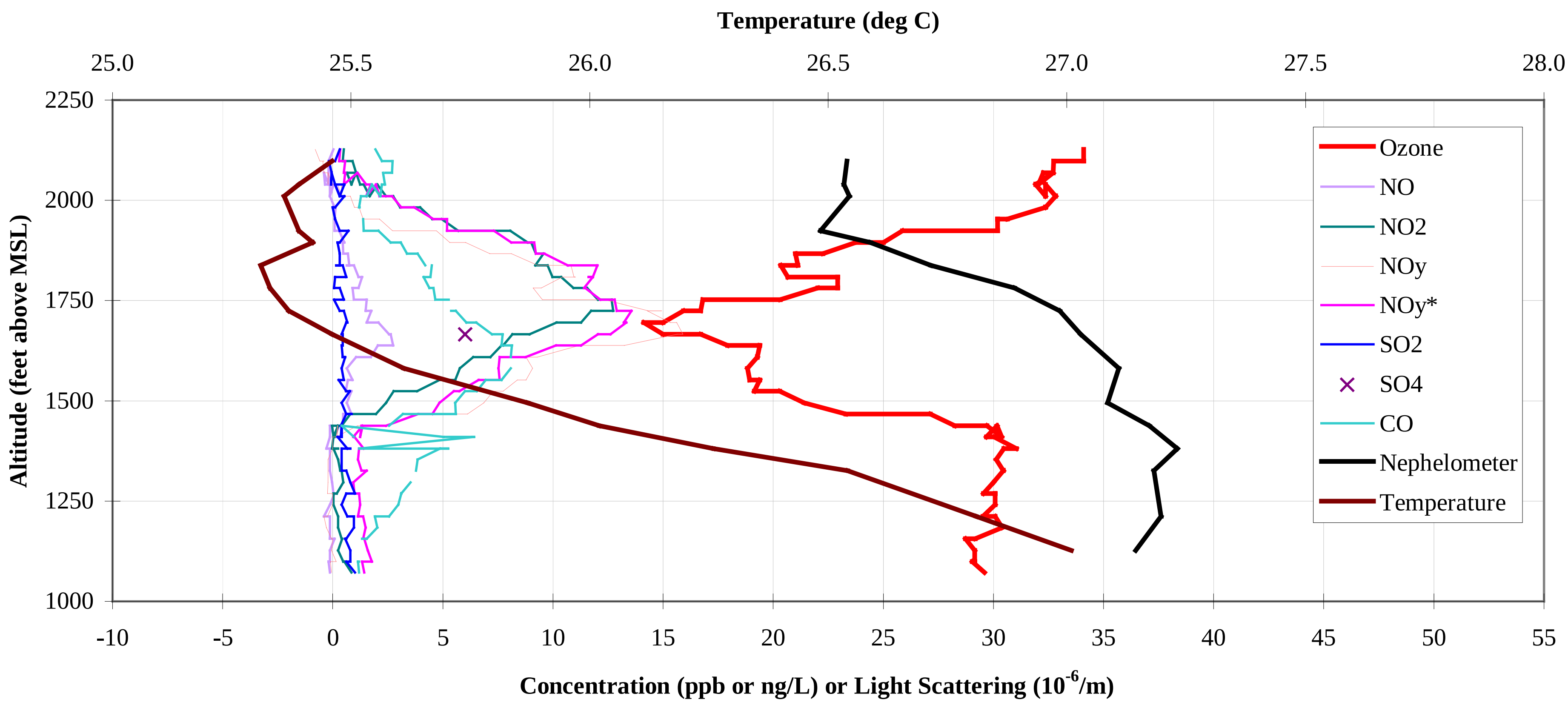


Figure 5-55b. Vertical profile of air quality and temperature data collected over La Porte, Texas, from 0638 to 0640 CST on August 29, 2000.

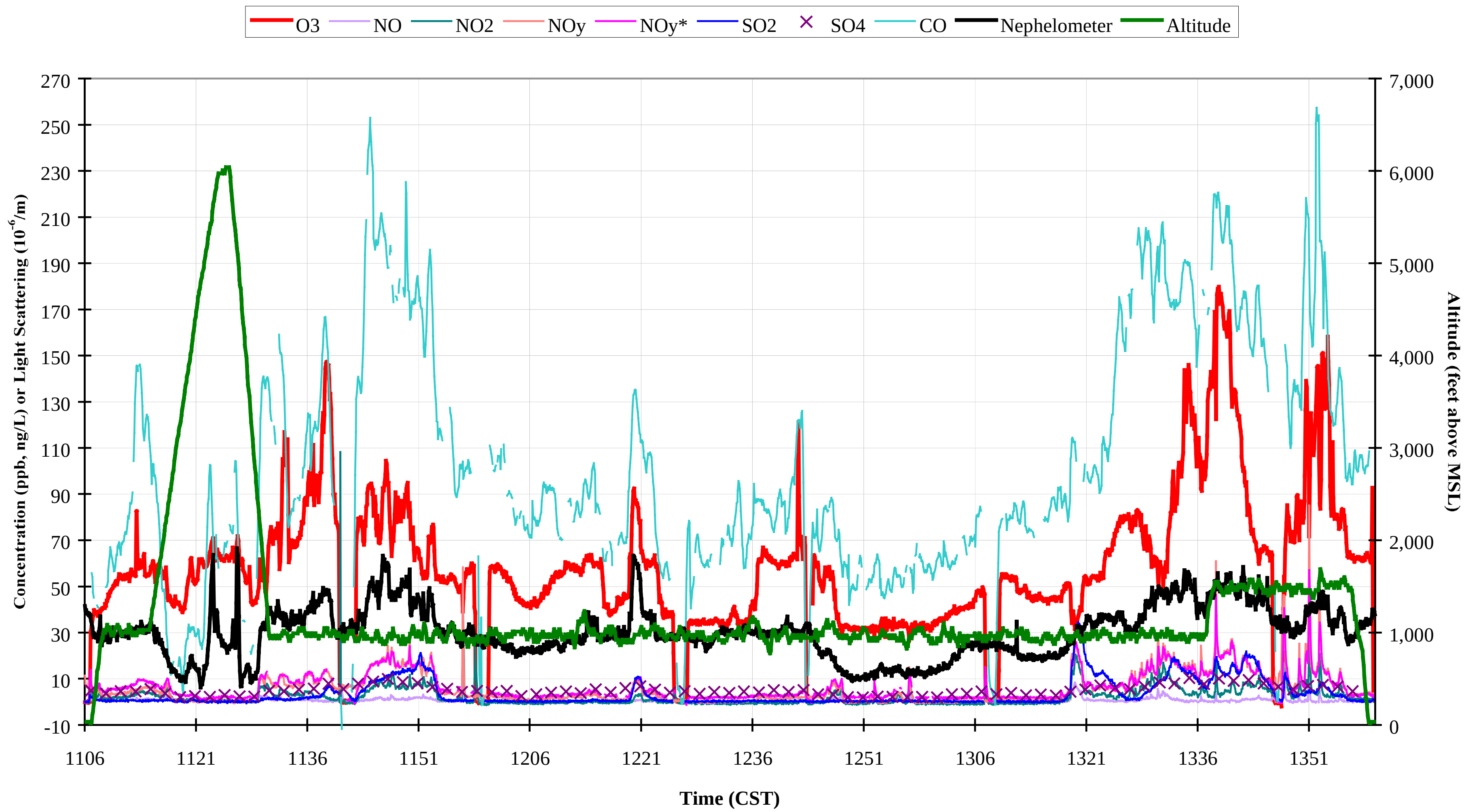


Figure 5-56. Time-series plot of air quality data collected from 1106 to 1400 CST on August 29, 2000.

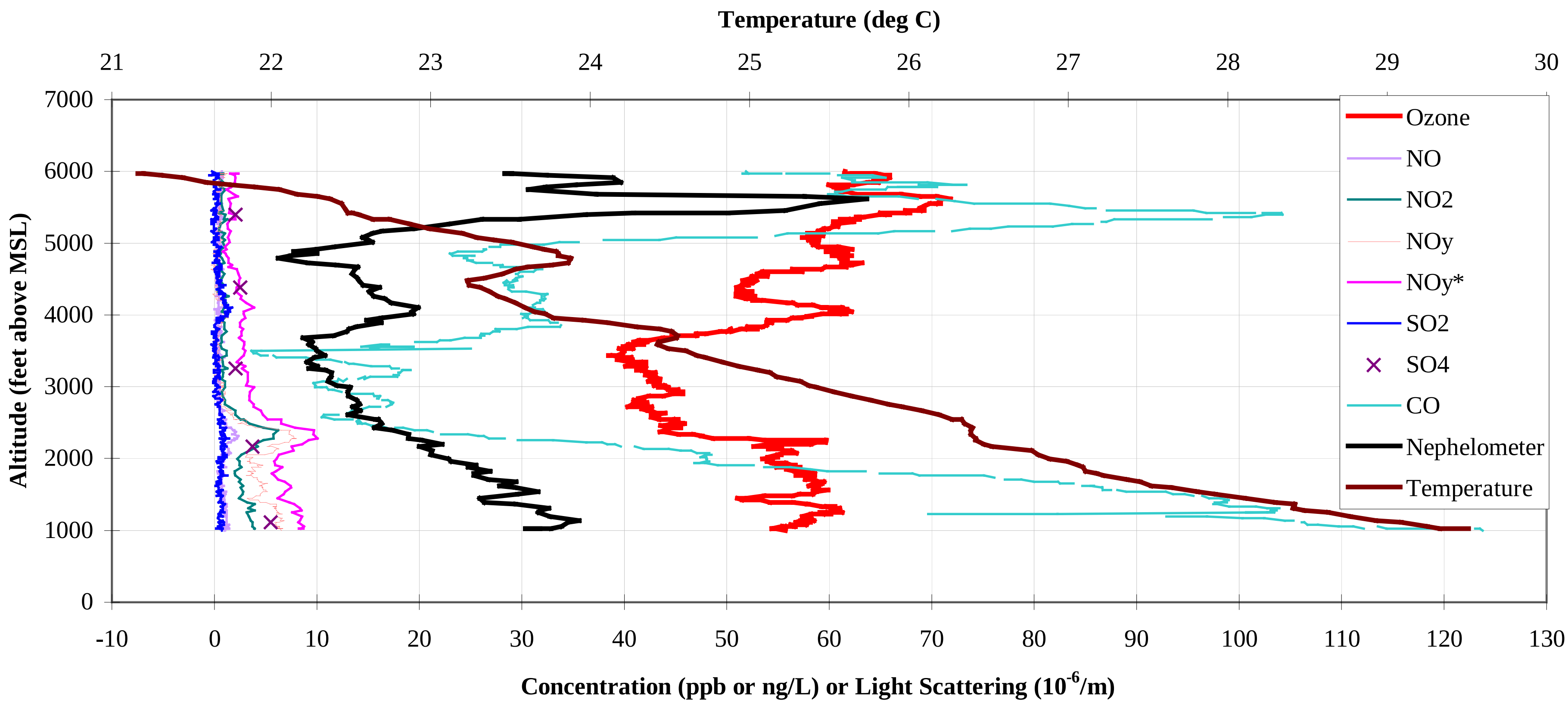


Figure 5-57. Vertical profile of air quality and temperature data collected over Galveston Bay from 1114 to 1125 CST on August 29, 2000.

5.7 FLIGHT 144A AND 144B, AUGUST 30, 2000

On August 30, 2000, there was a morning and a late morning/afternoon flight. The morning flight consisted of a series of box climbs up to approximately 2000 ft msl (610 m msl) along with one box climb to 10,000 ft msl (3050 m msl) east of Texas City (**Figure 5-58**). When box climbs were not being flown, the flight path was maintained at approximately 1000 ft msl (305 m msl). The late morning/afternoon flight was confined to southeast and central Houston with a single box climb over Galveston Bay to 5000 ft msl (1524 m msl) and several traverses at 1000 ft msl (105 m msl) over eastern Houston near the Ship Channel (**Figure 5-59**). The afternoon flight was flown prior to the peak surface ozone concentrations.

5.7.1 Overview of Meteorology and Air Quality

There was a broad ridge of high pressure at 500 mb over the eastern United States with anticyclonic flow over Texas and the Houston area (**Figure 5-60a**). At the surface, there was a low-pressure area over the eastern Gulf of Mexico (**Figure 5-60b**).

In the lowest 1640 ft msl (500 m msl) the radar profiler winds showed a period of westerly winds during the early morning hours, followed by northwesterly winds through 1300 CST **(Figure 5-61**). The winds then become light and variable between 1300 and 1700 CST, followed by the onset of the Gulf Breeze at 1700 CST. There did not appear to be a Bay Breeze on this day, and the midday stagnation followed by the Gulf Breeze started later than usual. In addition, unlike conditions on previous flight days, e.g., August 29, 2000, recirculation did not appear to play a major role in the high ozone concentrations observed throughout the Houston area on August 30. Rather, the high concentrations were probably related to midday stagnation.

As shown in **Figure 5-62**, the boundary layer depth, as estimated by profiler reflectivity data (C_n^2) at Ellington Field, was approximately 984 ft msl (300 m msl) during the overnight hours through 0900 CST (1500 UTC). Beginning around 0900 CST (1500 UTC), the mixing heights gradually increased, reaching 3280 ft msl (1000 m msl) by 1300 CST (1900 UTC). The mixing heights then increased rapidly, reaching 6560 ft msl (2000 m msl) at 1600 CST (2200 UTC). Mixing heights began to decrease around 1700 CST (2300 UTC), at which time the Gulf Breeze was observed at Ellington Field. The aircraft box climb east of Texas City showed an inversion at 0800 CST from 1000 to 2000 ft msl (304 to 610 m msl) (**Figure 5-63**). This inversion height agreed with the C_n^2 estimated mixing height at that time of about 984 ft msl (300 m msl). The box climb over Galveston Bay at 1130 CST showed a strong temperature inversion at 2000 ft msl corresponding to the mixing height of 2296 ft msl (700 m msl) observed at 1130 CST (1730 UTC) in the C_n^2 data.

The highest ozone concentrations occurred in the vicinity of the Houston Ship Channel, with lower concentrations in central Houston, as observed at surface CAMS sites and by the aircraft.

5.7.2 Spatial Observations of Ozone and NO_x

Morning Horizontal

- During the early morning hours, surface ozone concentrations were titrated at all sites, with concentrations ranging from near 0 to 20 ppb. Morning NO_x concentrations ranged from 80 ppb at CAMS 403 (near the Ship Channel) to around 10 ppb at outlying sites such as CAMS 26 (northwest of Houston).
- As shown in **Figure 5-63**, carryover ozone concentrations, observed during the morning box climb east of Texas City above the morning mixed layer (2000 ft msl or 610 m msl) and below the maximum daytime mixing height (6000 ft msl or 1829 m msl), were about 60 ppb. The 24-hr EDAS back-trajectories indicate that the air at 700 m agl originated from just offshore over the Gulf of Mexico, and the air at 1500 m agl originated from Louisiana (**Figure 5-64**).

Morning Vertical

- Although the exact structure of the pollutants varies among morning box climbs, as with other morning flights several morning box climbs showed several different pollutant layers and inversions. An example of such a box climb is shown in **Figures 5-65 and 5-66**, the La Porte box climb. As shown in Figure 5-65, there was a temperature inversion at around 1000 ft msl or (305 m msl). Beneath the inversion, ozone concentrations were around 10 to 20 ppb. Within the inversion (Figure 5-66), there was a layer of NO_y (105 ppb at 1100 ft msl or 335 m msl) and NO (75 ppb at 1100 ft msl or 335 m msl), with low ozone concentrations (5 ppb at 1100 ft msl or 335 m msl). Collocated SO_2 concentrations were almost 70 ppb. Above the inversion, NO_y, NO, and SO_2 concentrations decreased to near 0 ppb and ozone concentrations increased to about 45 ppb. Winds at this level were from the west-southwest for several hours at the time of the box climb.
- There was a deep morning box climb east of Texas City (Figure 5-63); above 1600 ft msl (487 m msl), ozone, NO_y, SO_2, and NO concentrations were about 60 ppb, 3 ppb, 0 to 1 ppb, and 0 to 1 ppb, respectively. From 1000 to 1600 ft msl (305 to 1829 m msl), there was a layer of NO_y, NO, and SO_2, and ozone was titrated. This layer may be the same layer observed during the La Porte box climb.

Late Morning/Afternoon Horizontal

- The highest surface ozone concentration was 195 ppb at CAMS 608 at 1600 CST near La Porte. Five CAMS sites reported ozone concentrations in excess of 150 ppb; most sites were located near the Ship Channel. CAMS 10 near Texas City reported a peak ozone concentration of 165 ppb at 1600 CST. In general, the sites nearest the Ship Channel had the highest peak ozone concentrations, with peaks south of the Ship Channel occurring around 1600 CST and peaks just north of the Ship Channel occurring around 1700 CST. Sites further north of the Ship Channel reached their peak ozone concentrations an hour or two later as the Gulf Breeze filled in. The highest ozone concentration observed by the aircraft was around 120 ppb at 1000 ft msl (305 m msl) just south/southwest of the Ship Channel (Figure 5-59 and **Figure 5-67**) at 1400 CST. This peak coincided with local NO_y and SO_2 concentration peaks of 15 and 10 ppb, respectively.

Afternoon Vertical

- As shown in **Figure 5-68**, the only box climb during the afternoon flight showed that ozone concentrations over Galveston Bay were 50 ppb at 1000 to 1250 ft msl (305 to 381 m msl), increasing to about 65 ppb from 1250 to 1800 ft msl (381 to 550 m msl). In these layers NO_y and NO concentrations are about 15 ppb and 2 to 4 ppb, respectively. At 1800 ft msl (550 m msl), a strong temperature inversion was observed, above which ozone concentrations were about 60 ppb, and NO_y and NO concentrations were near 0 ppb. This air was probably regional background.
- In Figures 5-59 and 5-67, a series of traverses over the region north of the Ship Channel revealed ozone concentrations of around 90 to 1100 ppb at 1335 to 1355 CST at an elevation of 1000 ft msl (305 m msl). NO_y and SO_2 concentration spikes were also observed within this time frame, suggesting a possible connection with point source emissions such as coal-fired plants. The highest ozone concentrations of 120 ppb at 1000 feet msl (305 m msl) were observed just prior to landing at Ellington Field. NO_y and SO_2 concentrations were about 20 ppb in this area.

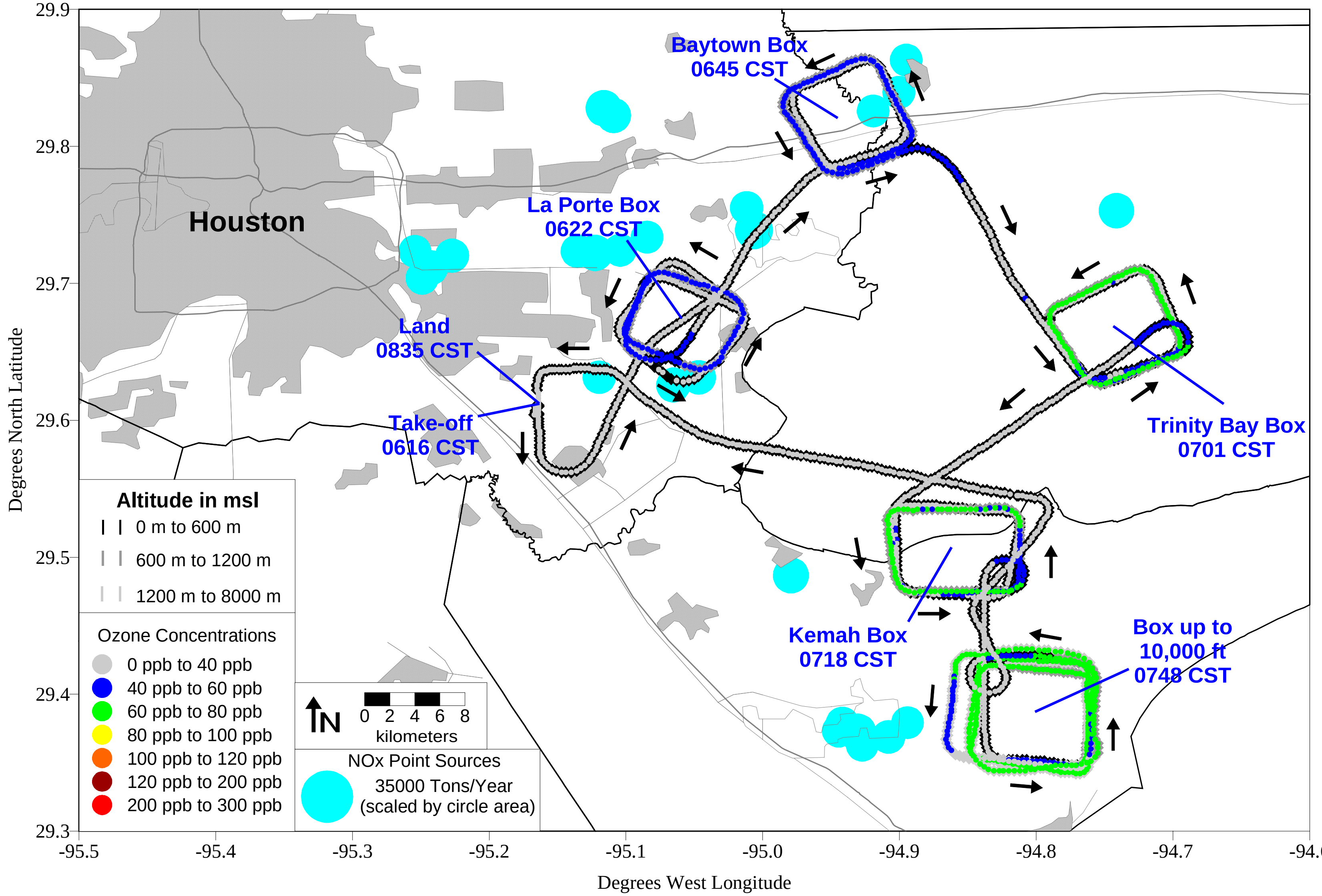


Figure 5-58. Flight 144 flight position, altitude, and aloft ozone concentrations on the morning of August 30, 2000.

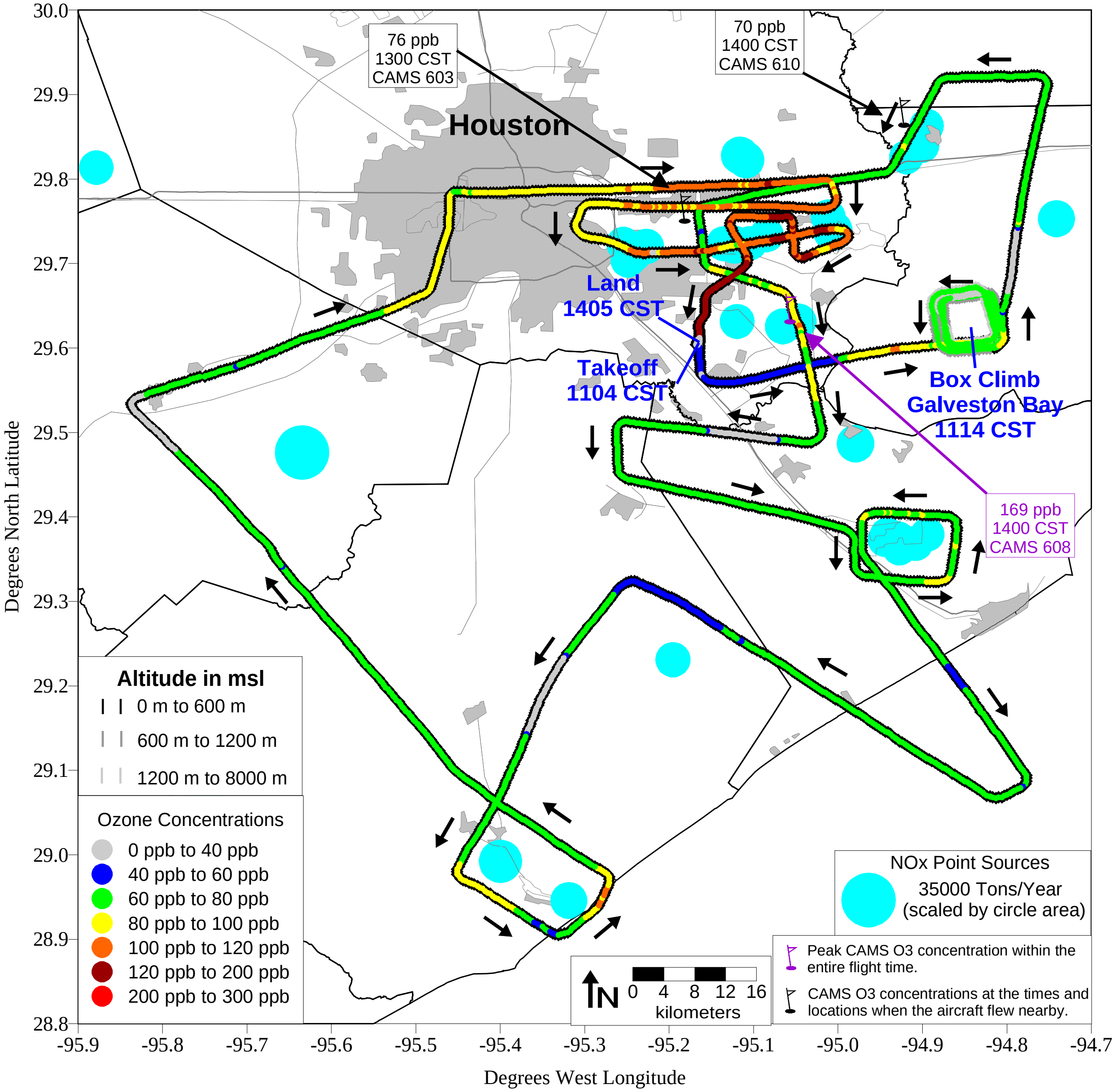


Figure 5-59. Flight 144 flight position, altitude, aloft ozone concentrations, and CAMS surface ozone concentrations on the afternoon of August 30, 2000.

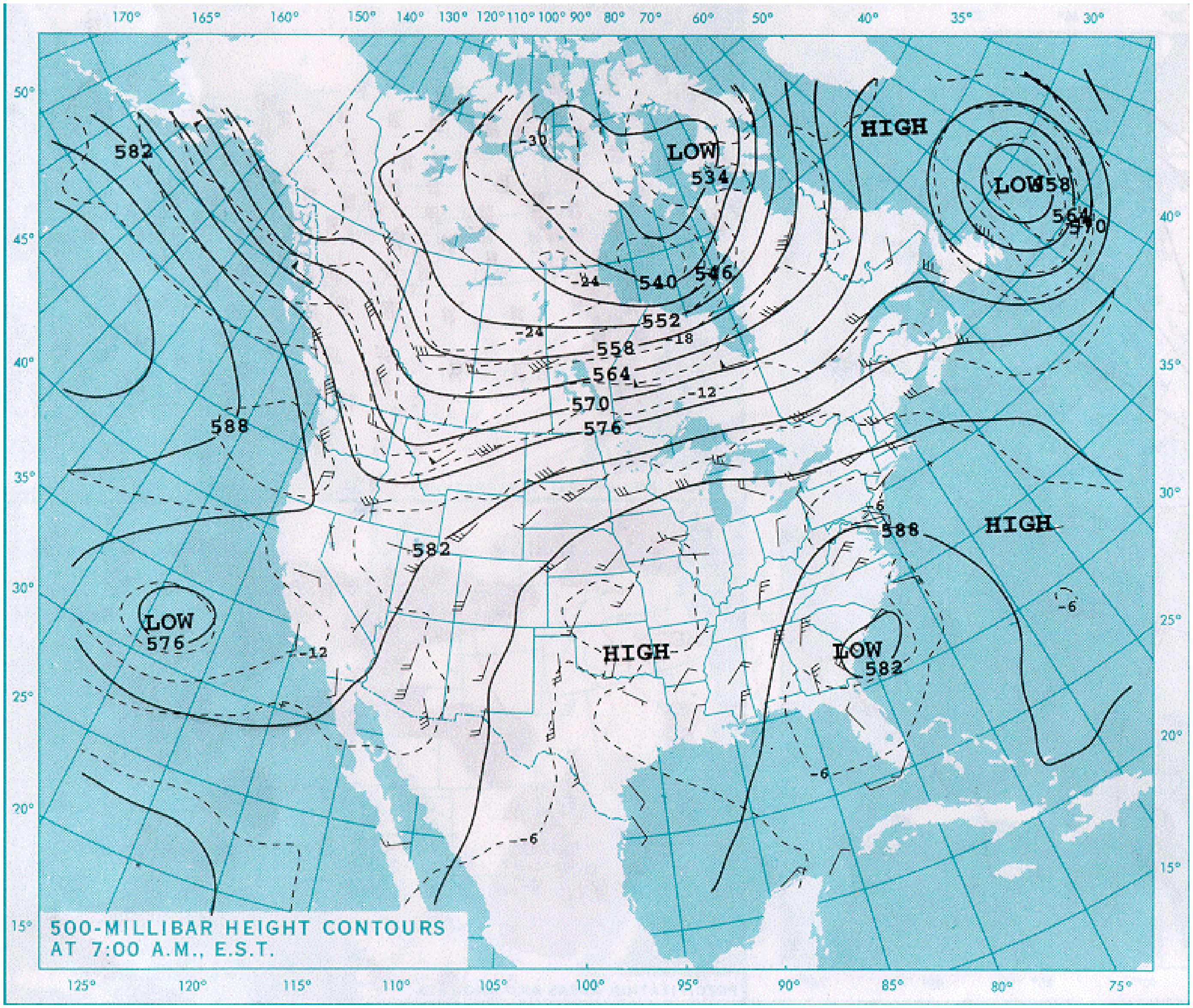


Figure 5-60a. Height contours of the 500-mb pressure surface at 0600 CST on August 30, 2000.

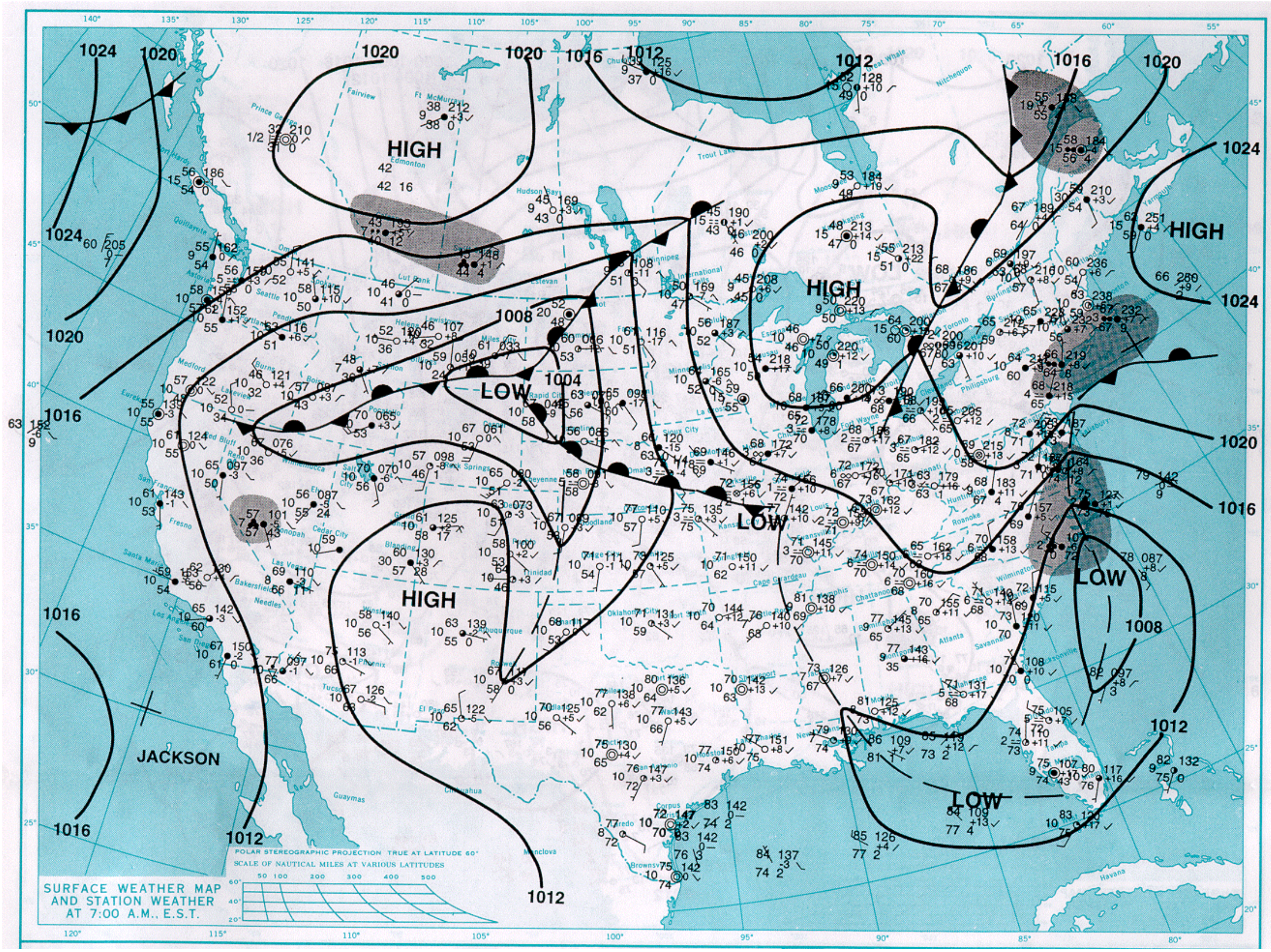


Figure 5-60b. Surface analysis at 0600 CST on August 30, 2000.

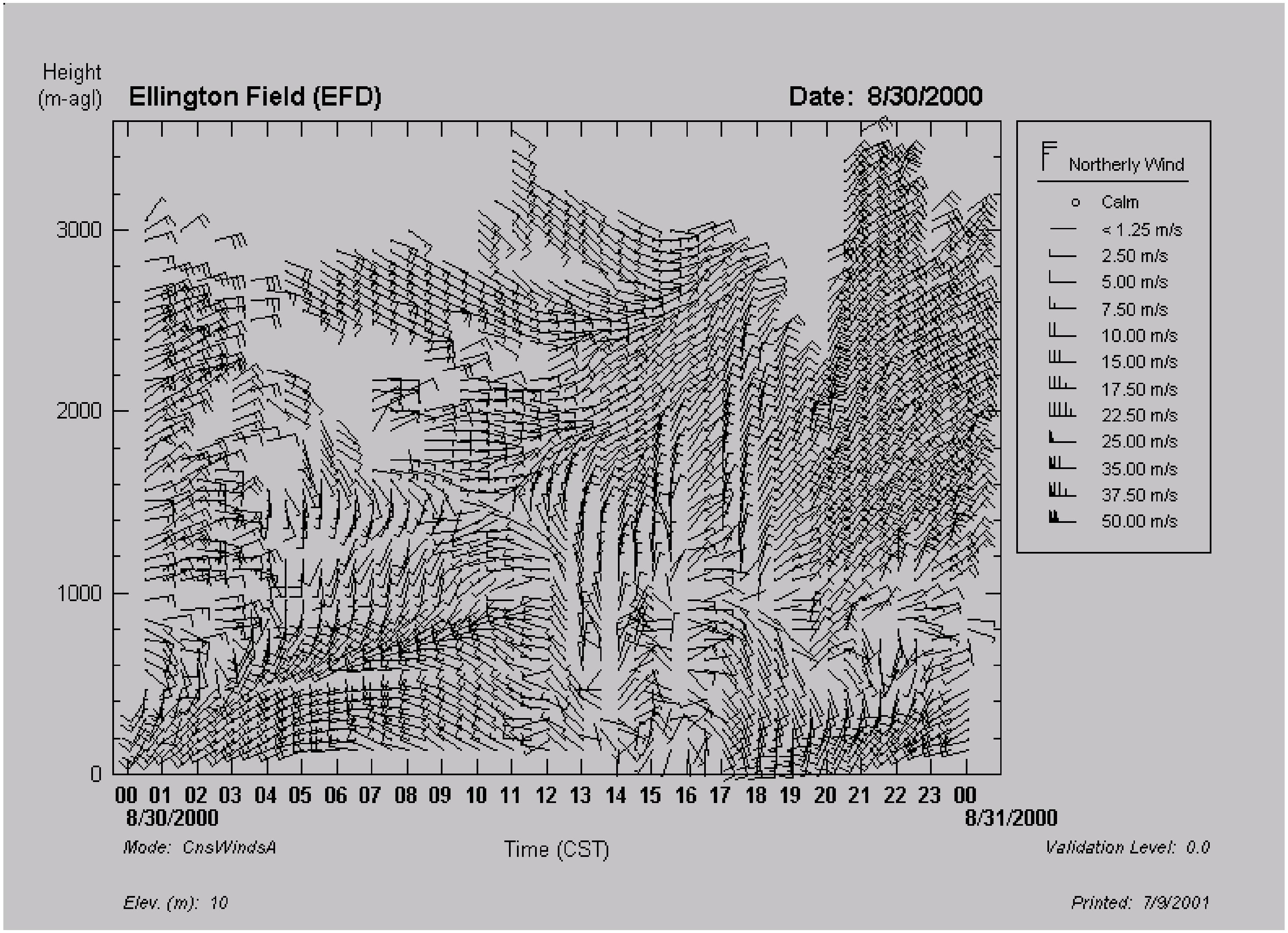


Figure 5-61. Radar wind profiler data for August 30, 2000 at Ellington Field, Houston. Note that the profiler is 10 m above msl.

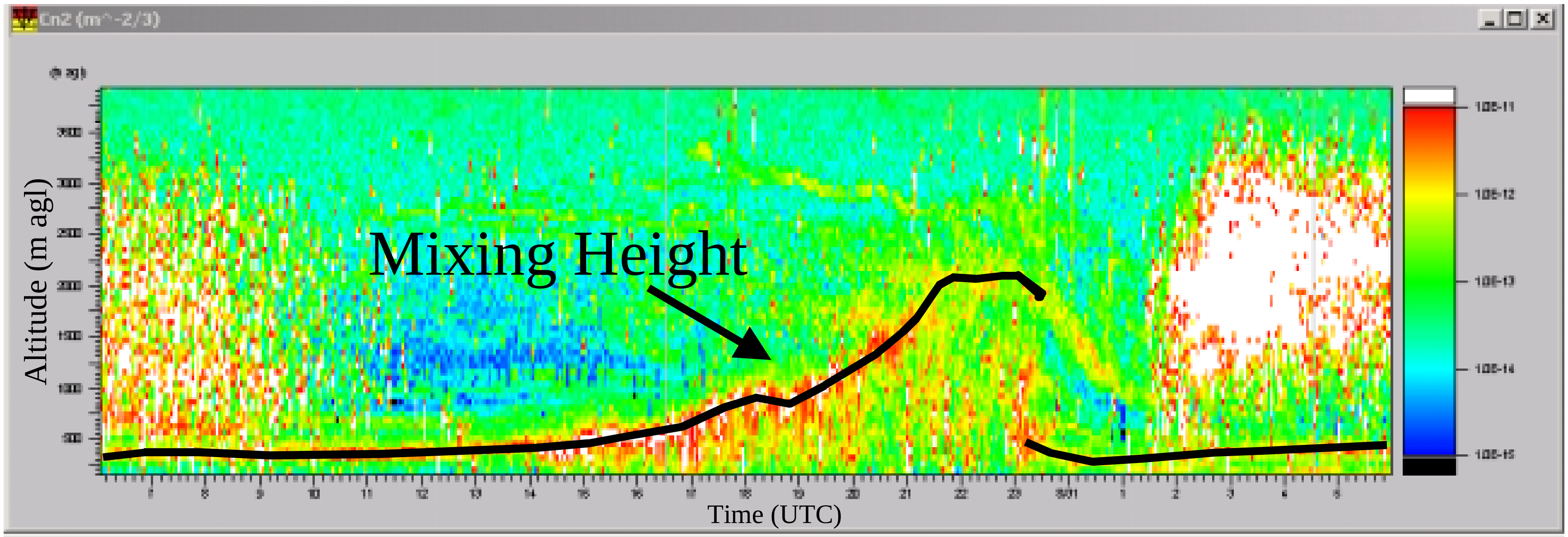


Figure 5-62. Radar wind profiler reflectivity data (C_n^2) and estimated mixing height for August 30, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

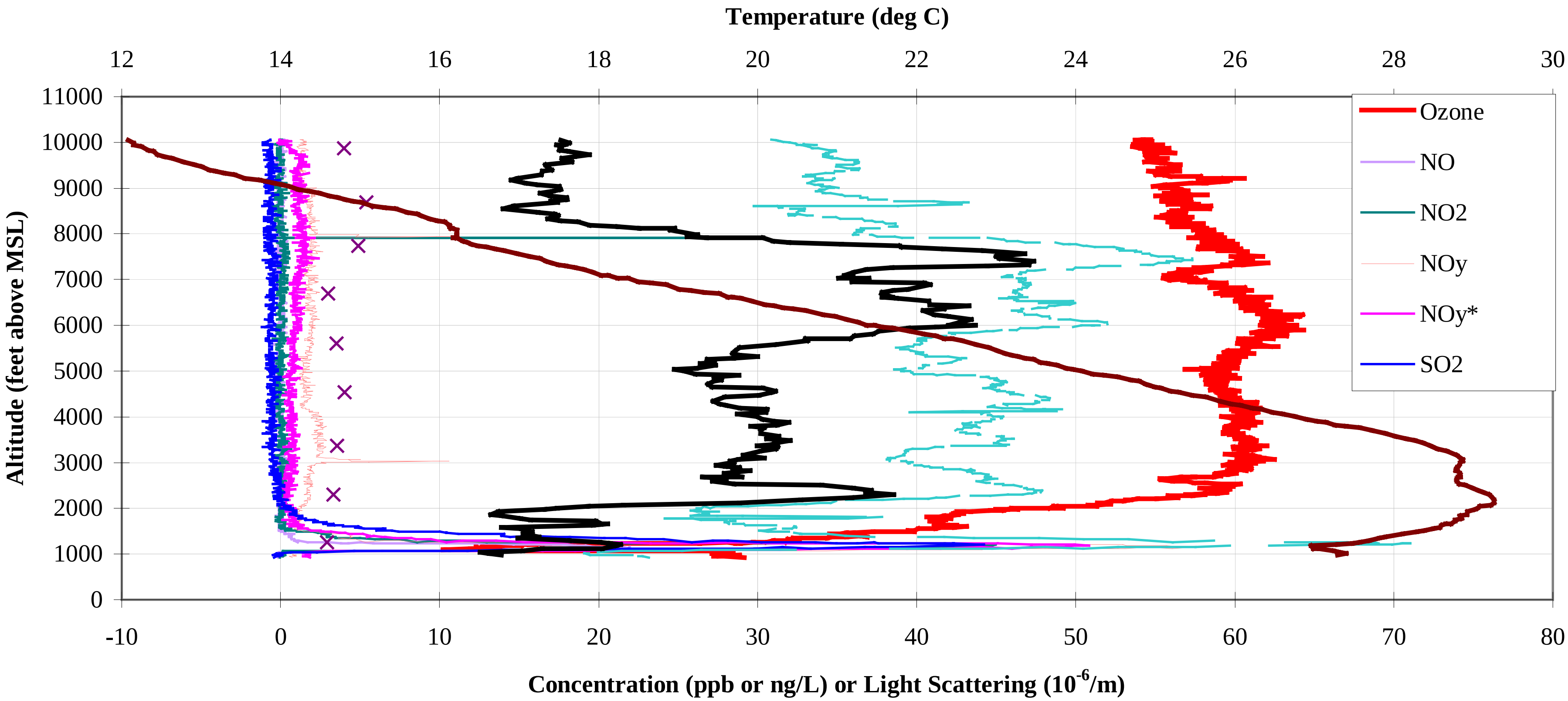


Figure 5-63. Vertical profile of air quality and temperature data collected over Galveston Bay (east of Texas City) from 0746 to 0805 CST on August 30, 2000.

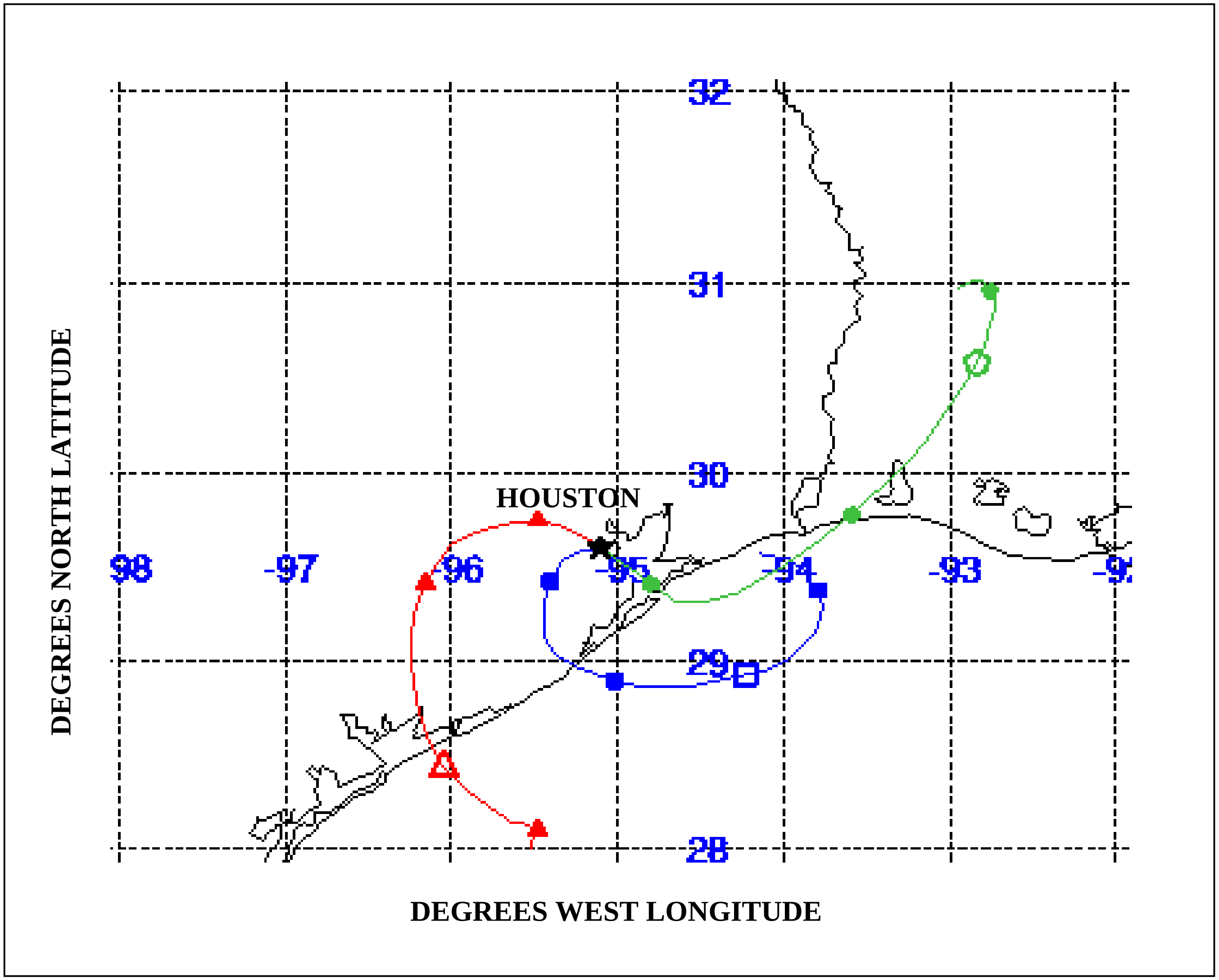


Figure 5-64. Twenty-four-hour back-trajectories for 140 m agl (red line), 700 m agl (blue line), and 1500 m agl (green line) from the general flight area in Houston on August 30, 2000, at 0900 CST.

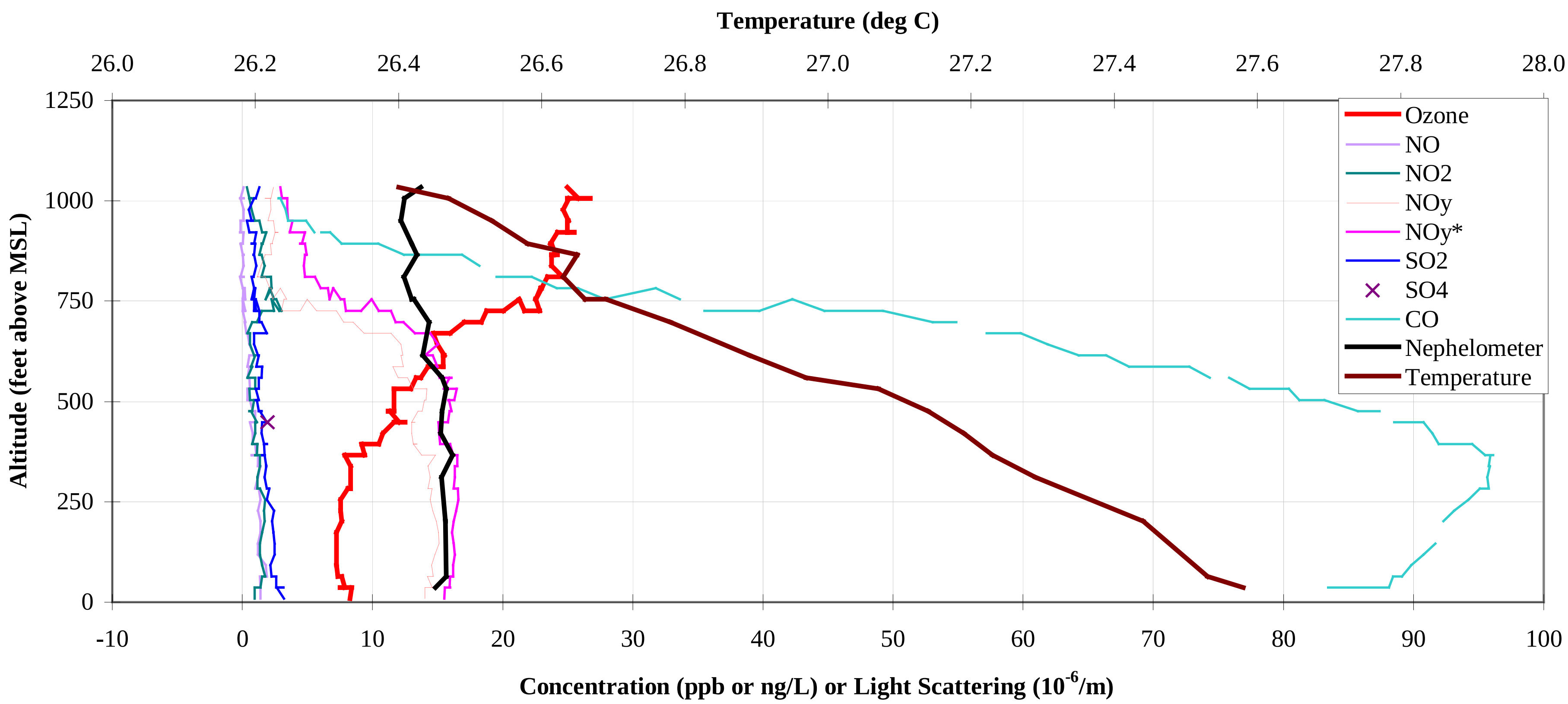


Figure 5-65. Vertical profile of air quality and temperature data collected over La Porte, Texas, from 0621 to 0623 CST on August 30, 2000.

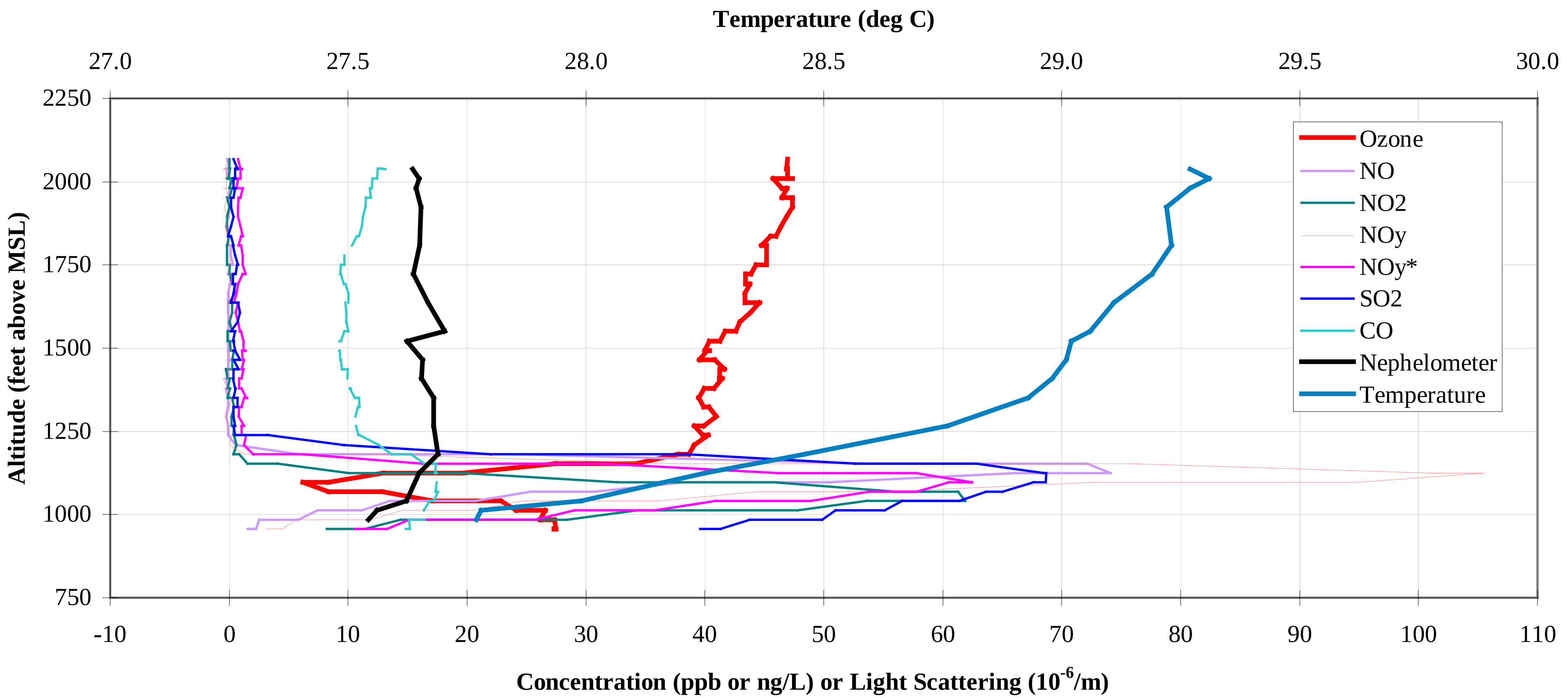


Figure 5-66. Vertical profile of air quality and temperature data collected over La Porte, Texas, from 0638 to 0640 CST on August 30, 2000.

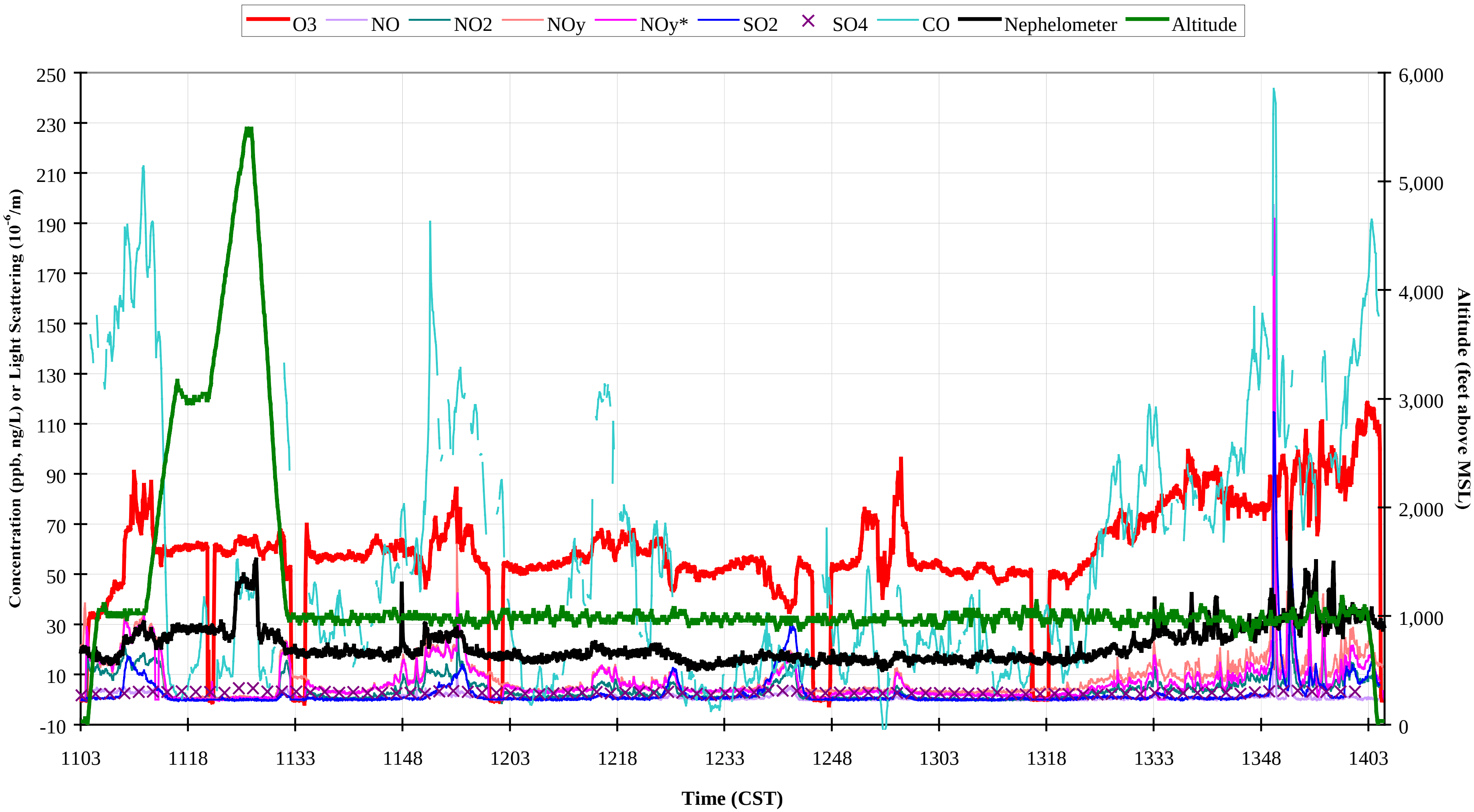


Figure 5-67. Time-series plot of air quality and temperature data collected from 1103 to 1405 CST on August 30, 2000.

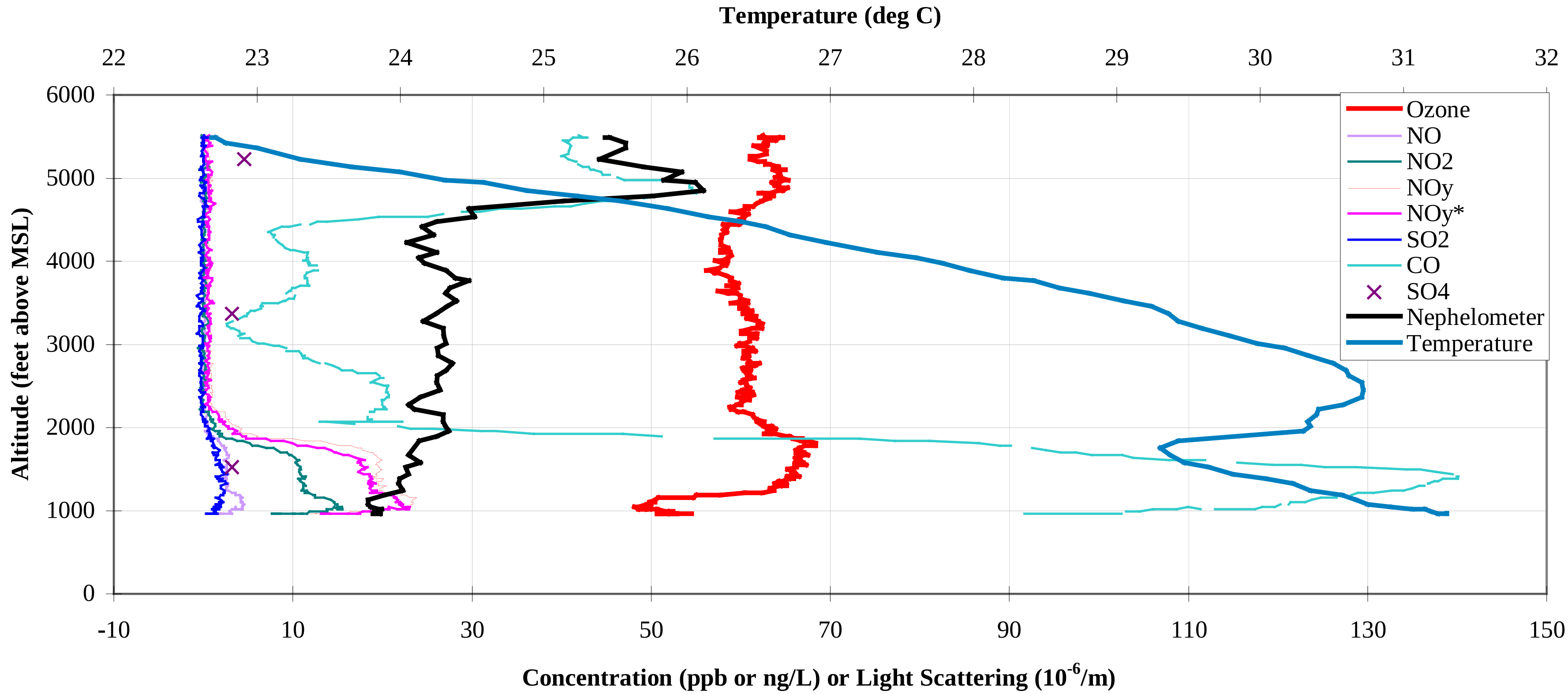


Figure 5-68. Vertical profile of air quality and temperature data collected over Galveston Bay from 1127 to 1133 CST on August 30, 2000.

5.8 FLIGHT 145A AND 145B, SEPTEMBER 1, 2000

On September 1, 2000, there was a morning and an afternoon flight. The morning flight consisted of three box climbs; one up to 2000 ft msl (610 m msl) over La Porte: one up to 4000 ft msl (1220 m msl) over Baytown; and one up to 6000 ft msl (1829 m msl) over Galveston Bay (**Figure 5-69**). When box climbs were not being flown, the flight altitude was maintained at about 1000 ft msl (304 m msl). The afternoon flight consisted of a pattern similar to the morning flight; however, a segment was flown over the Ship Channel at about 1500 ft msl (457 m msl) prior to landing, and the box climb over Galveston Bay was limited to 4500 ft msl (1372 m msl). Also, two segments were flown over Galveston Bay after the Galveston Bay box climb in both the morning and afternoon flights (**Figure 5-70**).

5.8.1 Overview of Meteorology and Air Quality

There was a broad ridge of high pressure at 500 mb over the eastern United States, extending down through Texas with a similar high-pressure area over Texas (**Figure 5-71**). This feature was observed on the previous day as well. However, on September 1, there was a surface low-pressure trough located over the Lake Charles, Louisiana, area.

The mixing heights, as estimated by profiler reflectivity data (C_n^2) at Ellington Field (**Figure 5-72**), were around 984 ft msl (300 m msl) during the morning hours through 0900 CST (1500 UTC). Beginning at approximately 0900 CST (1500 UTC), the mixing height gradually increased to 1640 ft msl (500 m msl) and remained at that height through 1130 CST (1730 UTC). The mixing heights then increased rapidly, reaching 9184 ft msl (2800 m msl) at 1600 CST (2200 UTC). The aircraft box climb over Galveston Bay during the morning flight showed an inversion at 1120 CST at around 2000 ft msl (610 m msl), which agreed with the C_n^2 estimated mixing depth of about 2100 ft msl (640 m msl) at that time (**Figure 5-73**).

Below 3280 ft msl (1000 m msl), the radar profiler winds and the back-trajectories indicate a period of westerly winds through 1000 CST, followed by southwesterly winds through 1700 CST (Figure 5-70 and **Figure 5-74**). High ozone concentrations occurred throughout the eastern Houston area probably due to transport from central Houston associated with the light westerly winds. The highest ozone concentrations were in the vicinity of Baytown as observed at surface CAMS sites and by the aircraft. Unlike conditions on previous days when the Bay/Gulf Breeze circulation cleaned out the high ozone concentrations late in the day, on this particular day, afternoon thunderstorms (due to the surface trough previously mentioned) cleaned out the region. Visible satellite imagery (**Figure 5-75**) revealed thunderstorms moving from the northeast to the southwest, reaching Houston at 1700 CST, precisely the time when a strong wind shift was observed by the Ellington Field radar wind profiler.

5.8.2 Characteristics of Ozone and NO_x

Morning Horizontal

- During the early morning hours surface ozone concentrations were titrated at all sites, with concentrations ranging from near 0 to 20 ppb. Morning NO_x concentrations ranged from 80 ppb at CAMS 403 (near the Ship Channel) to around 10 ppb at outlying sites such as CAMS 26 (northwest of Houston).

Morning Vertical

- **Figure 5-76** shows aloft ozone concentrations, as observed during a morning box climb over Baytown between 2000 and 4000 ft msl (610 and 1220 m msl), the top of the box climb, were about 80 ppb. The 700-m 24-hr EDAS back-trajectories indicate that the air at this level originated near Corpus Christi on the prior day, heading north toward San Antonio before going to Houston (**Figure 5-77**). Below 2000 ft msl (610 m msl), ozone, NO_y, NO, and SO_2 concentrations were about 50 to 70 ppb, 20 to 30 ppb, 5 ppb, and 0 ppb, respectively.
- Similar to other flights, the 2000-ft morning box climbs show several pollutant layers and inversions. An example box climb (La Porte) is shown in **Figure 5-78**. The figure shows a strong temperature inversion at around 1800 ft msl (550 m msl) and three distinct pollutant layers.
  - From 100 to 600 ft msl (30 to 183 m msl), ozone concentrations were 40 ppb, NO_y concentrations were 15 ppb, NO concentrations were 0 ppb, and SO_2 concentrations were near 0 ppb.
  - From 600 to 1600 ft msl (183 to 488 m msl), there was a layer of NO_y (20 to 25 ppb) and NO (0 to 12 ppb), but SO_2 was 0 ppb. For this layer, ozone concentrations fluctuated between 30 and 45 ppb. Radar profiler winds indicate that this layer probably came from central Houston toward La Porte.
  - Within the inversion, from 1600 to 2000 ft msl (488 to 610 m msl), the top of the box climb, there was another layer of NO and NO_y with concentrations of 5 to 10 ppb and 40 ppb, respectively; however, this layer also contained SO_2 concentrations of 10 to 15 ppb. Winds at this level were also westerly.

Afternoon Horizontal

- The highest surface ozone concentration was 160 ppb at CAMS 611 at 1300 CST near Baytown (not shown). Three CAMS sites reported ozone concentrations in excess of 100 ppb, all located near Baytown. There were five other CAMS sites, mostly near the Ship Channel, that observed ozone concentrations above 90 ppb. The highest ozone concentrations were observed at 1300 CST at most of the sites. The highest ozone concentration observed by the aircraft was about 135 ppb between 2000 and 3000 ft msl (610 and 915 m msl) over the Baytown area during the afternoon (1450 CST) Baytown box climb. This peak coincided with local NO_y and SO_2 concentration peaks of 20 and 5 ppb, respectively.

Afternoon Vertical

- The afternoon Galveston Bay box climb beginning at 1516 CST (**Figure 5-79**) shows that ozone concentrations were around 100 to 110 ppb between 1300 ft msl (396 m msl), the start of the climb, and 3000 ft msl (915 m msl). Ozone concentrations were about 120 ppb from approximately 3000 to 4000 ft msl (915 to 1220 m msl). The top of this box climb was 4500 ft msl (457 m msl), well below the top of the mixed layer. NO_y and NO concentrations of 10 to 20 ppb and 0 to 1 ppb, respectively, were observed throughout the profile, with a layer of higher concentrations at 1700 and 3500 ft msl (518 and 1068 m msl). The 700-m agl back-trajectories (Figure 5-70) indicate that this air originated earlier, at 1100 CST, just south of Ellington Field.

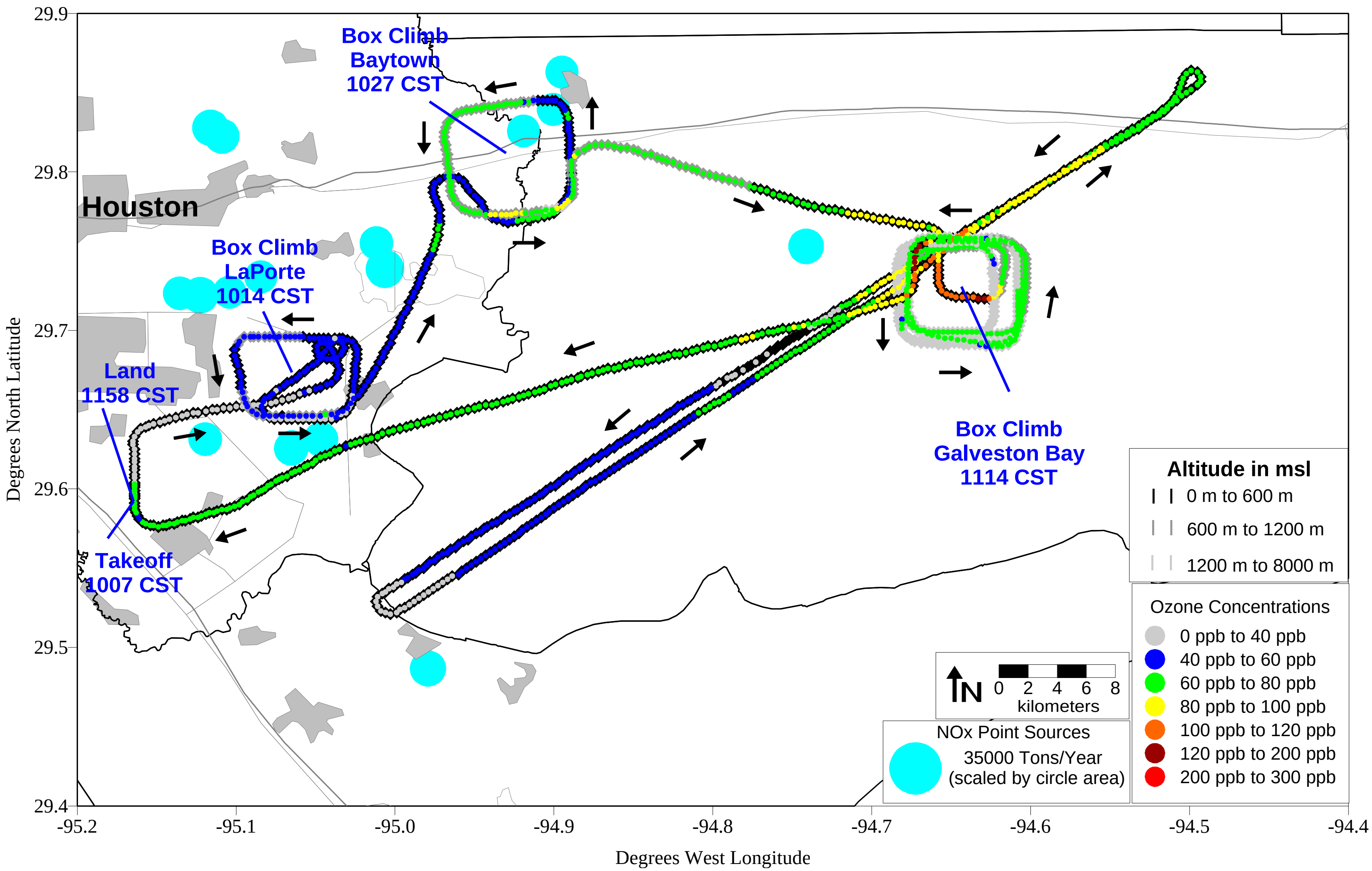


Figure 5-69. Flight 145 flight position, altitude, and aloft ozone concentrations on the morning of September 1, 2000.

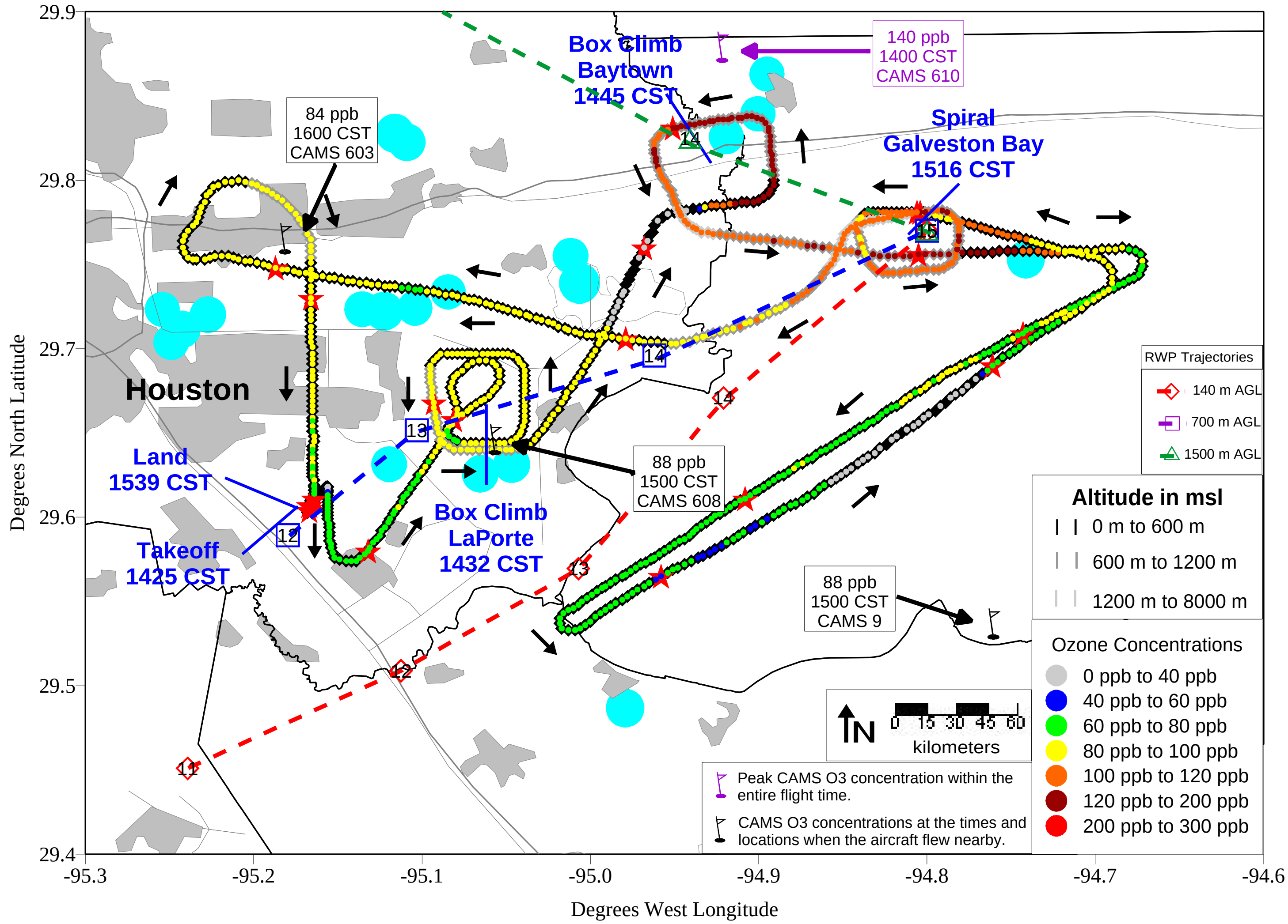


Figure 5-70. Flight 145 flight position, altitude, aloft ozone concentrations, CAMS surface ozone concentrations, and back-trajectories on the afternoon of September 1, 2000.

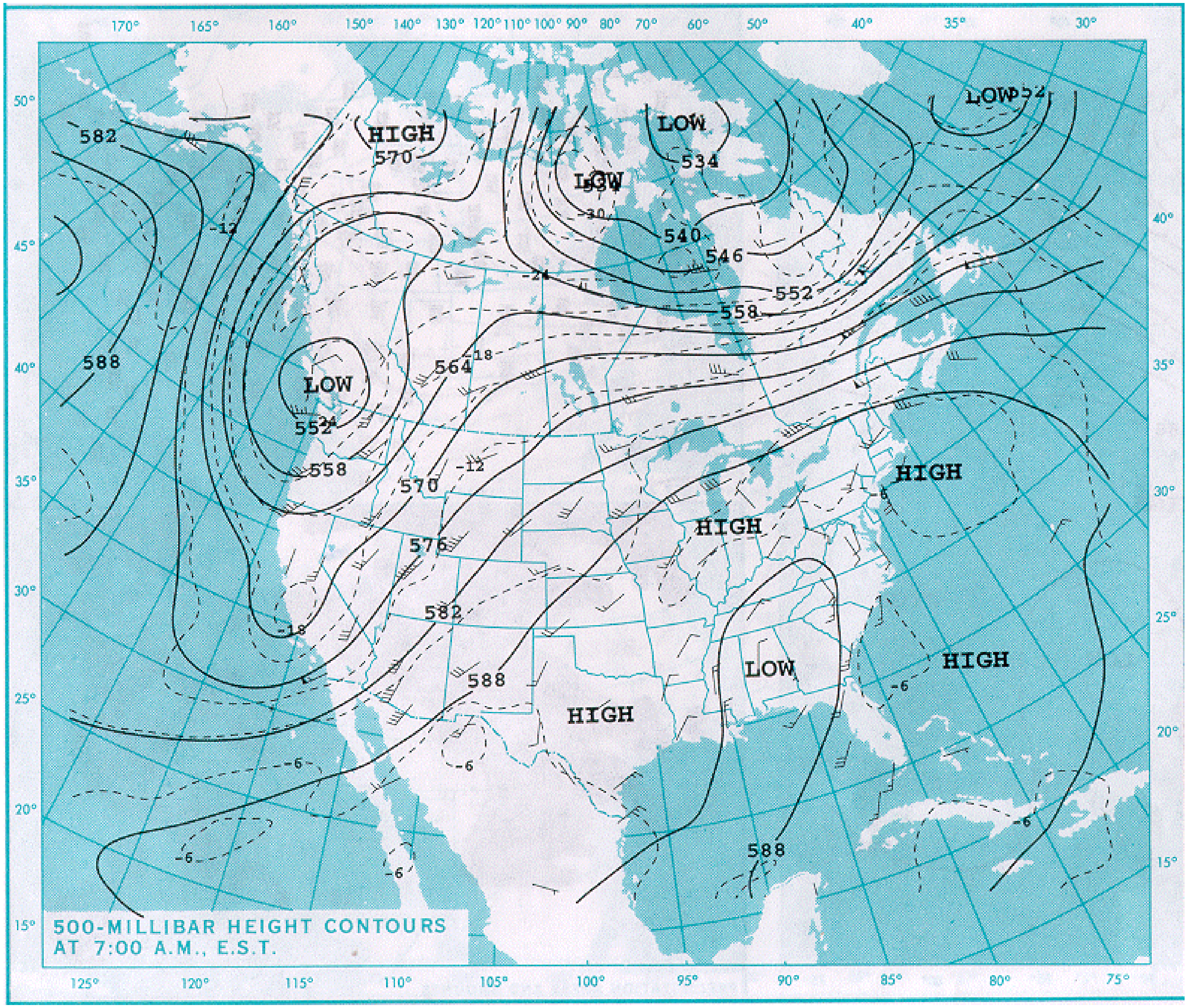


Figure 5-71. Height contours of the 500-mb pressure surface at 0600 CST on September 1, 2000.

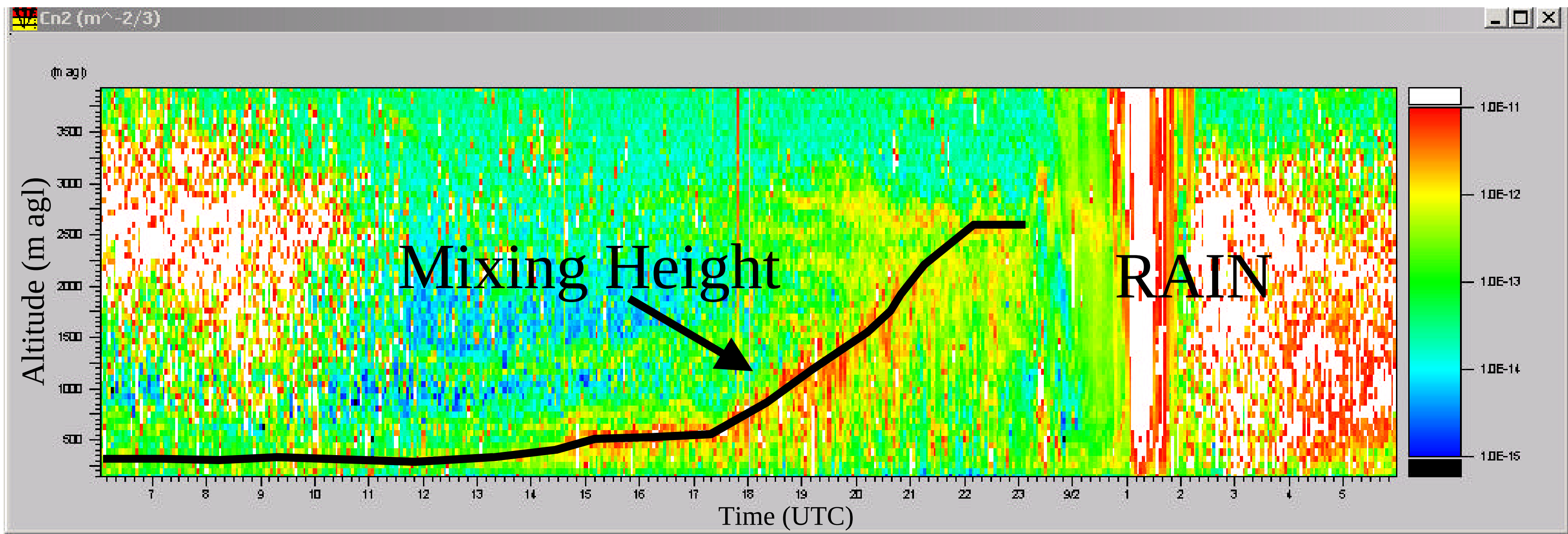


Figure 5-72. Radar wind profiler reflectivity data (C_n^2) and estimated mixing height for September 1, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

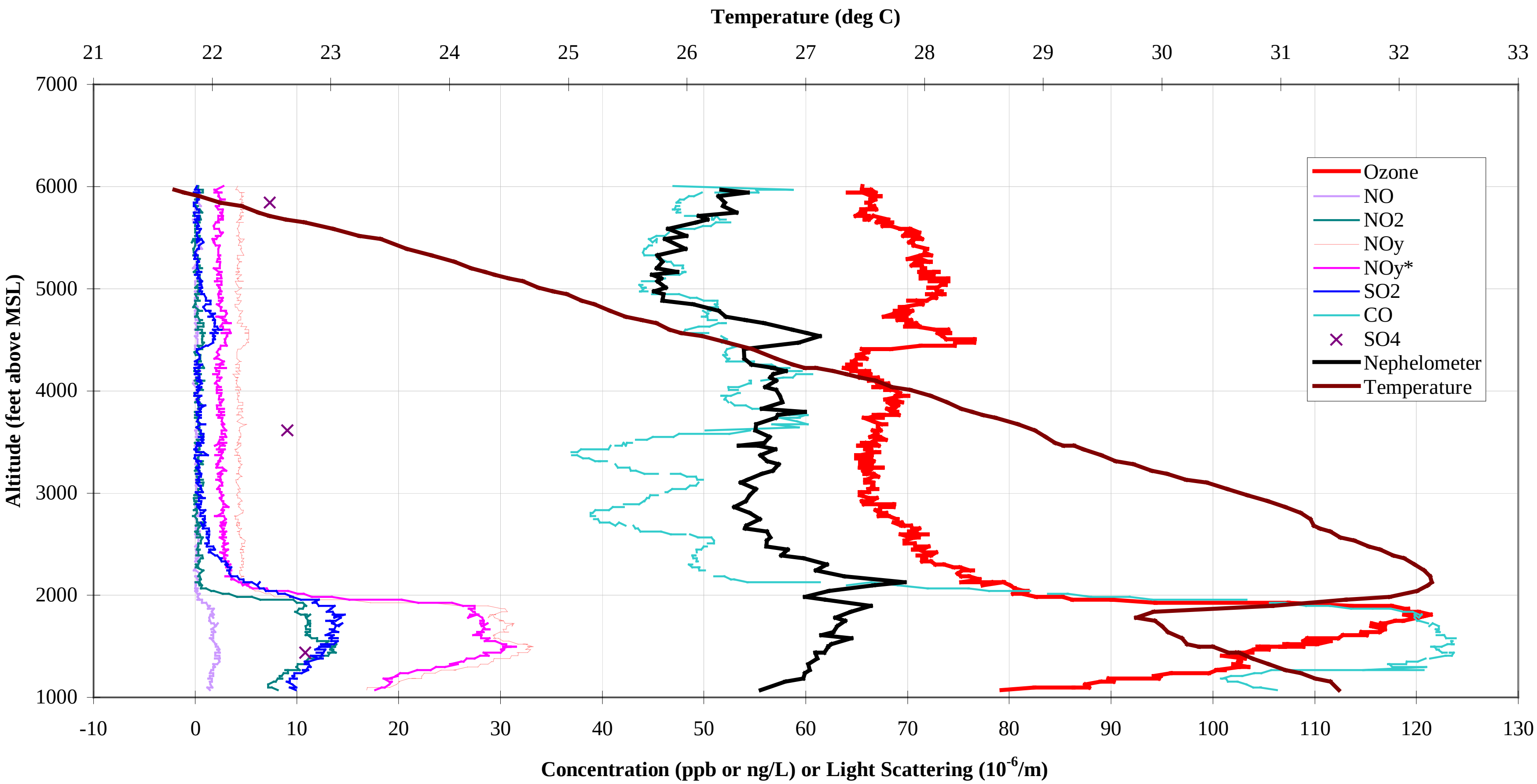


Figure 5-73. Vertical profile of air quality and temperature data collected over Galveston Bay from 1114 to 1124 CST on September 1, 2000.

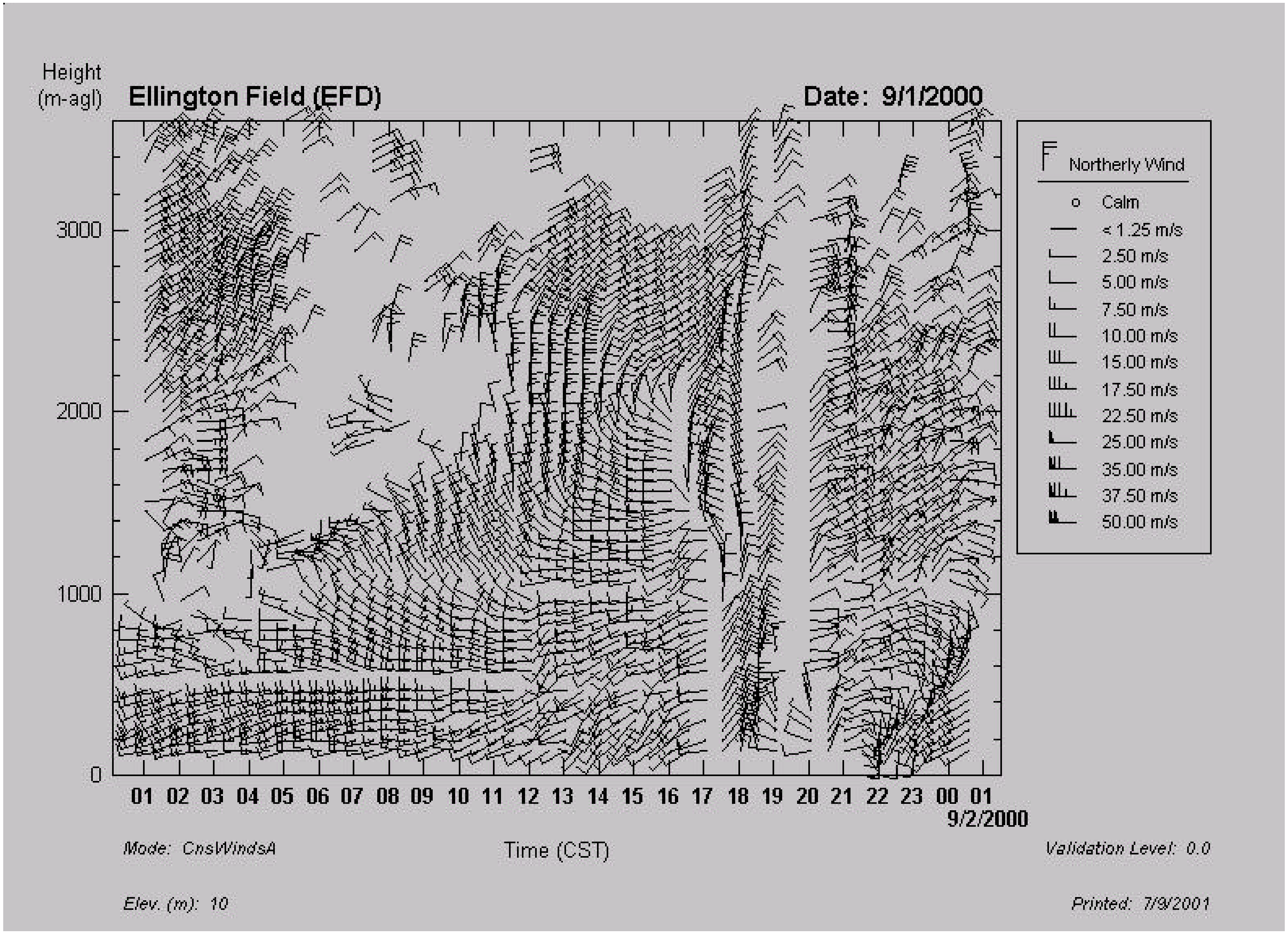


Figure 5-74. Radar wind profiler data for September 1, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

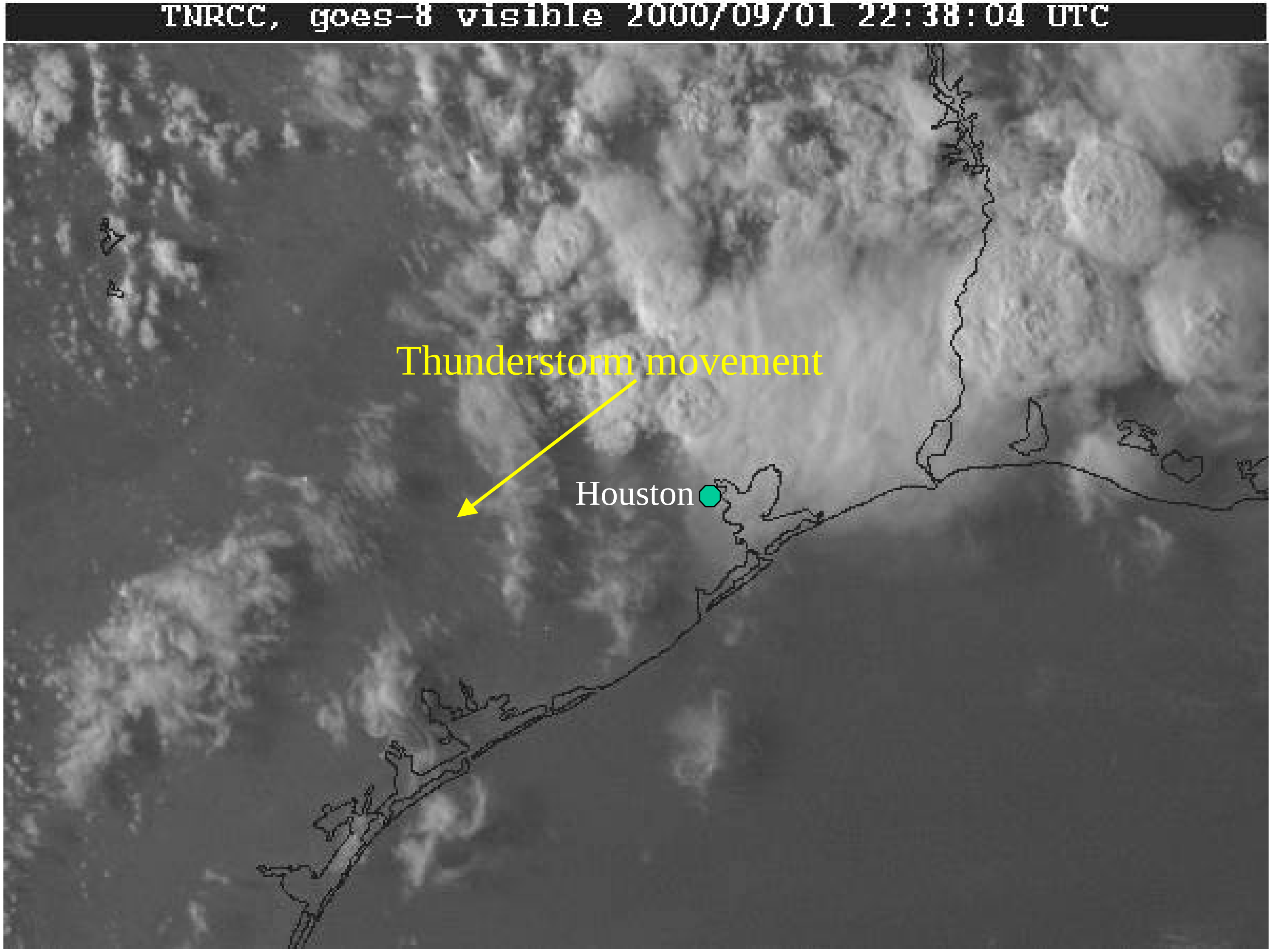


Figure 5-75. Visible satellite imagery at 1638 CST (2238 UTC) on September 1, 2000.

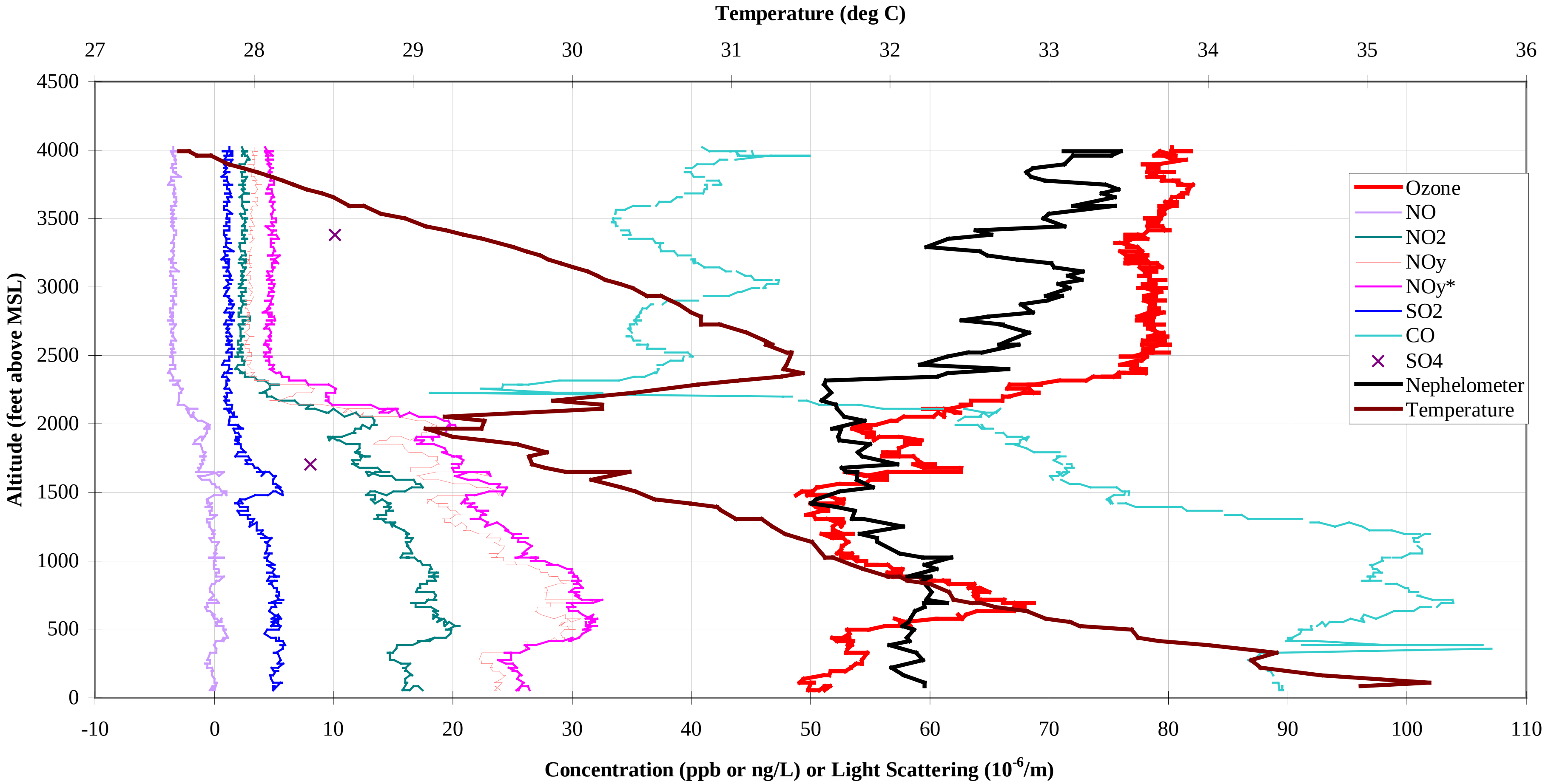


Figure 5-76. Vertical profile of air quality and temperature data collected over Baytown from 1027 to 1037 CST on September 1, 2000.

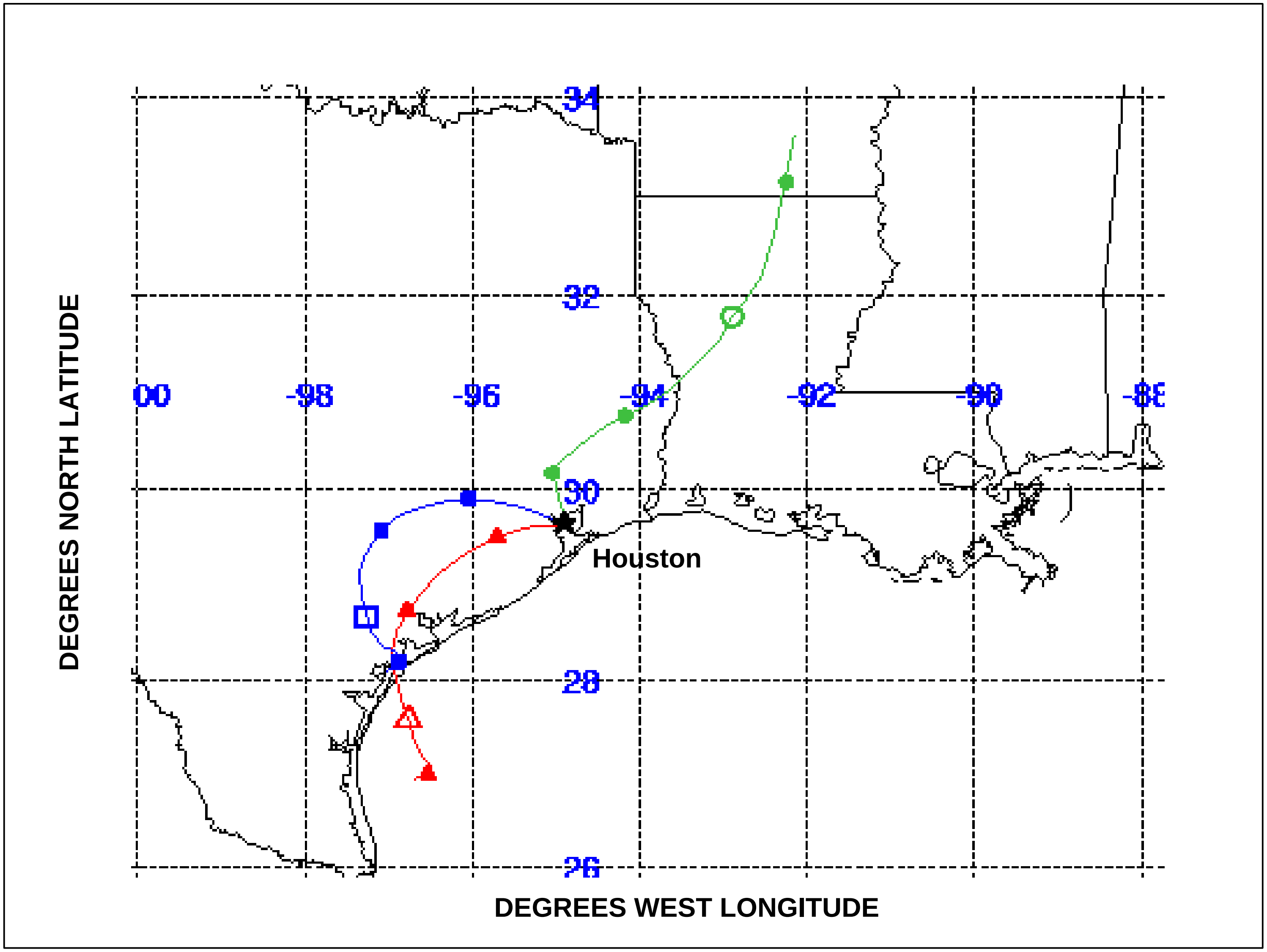


Figure 5-77. Twenty-four-hour EDAS back-trajectories for 140 m agl (red line), 700 m agl (blue line), and 1500 m agl (green line) from the general flight area in Houston on September 1, 2000, at 1000 CST.

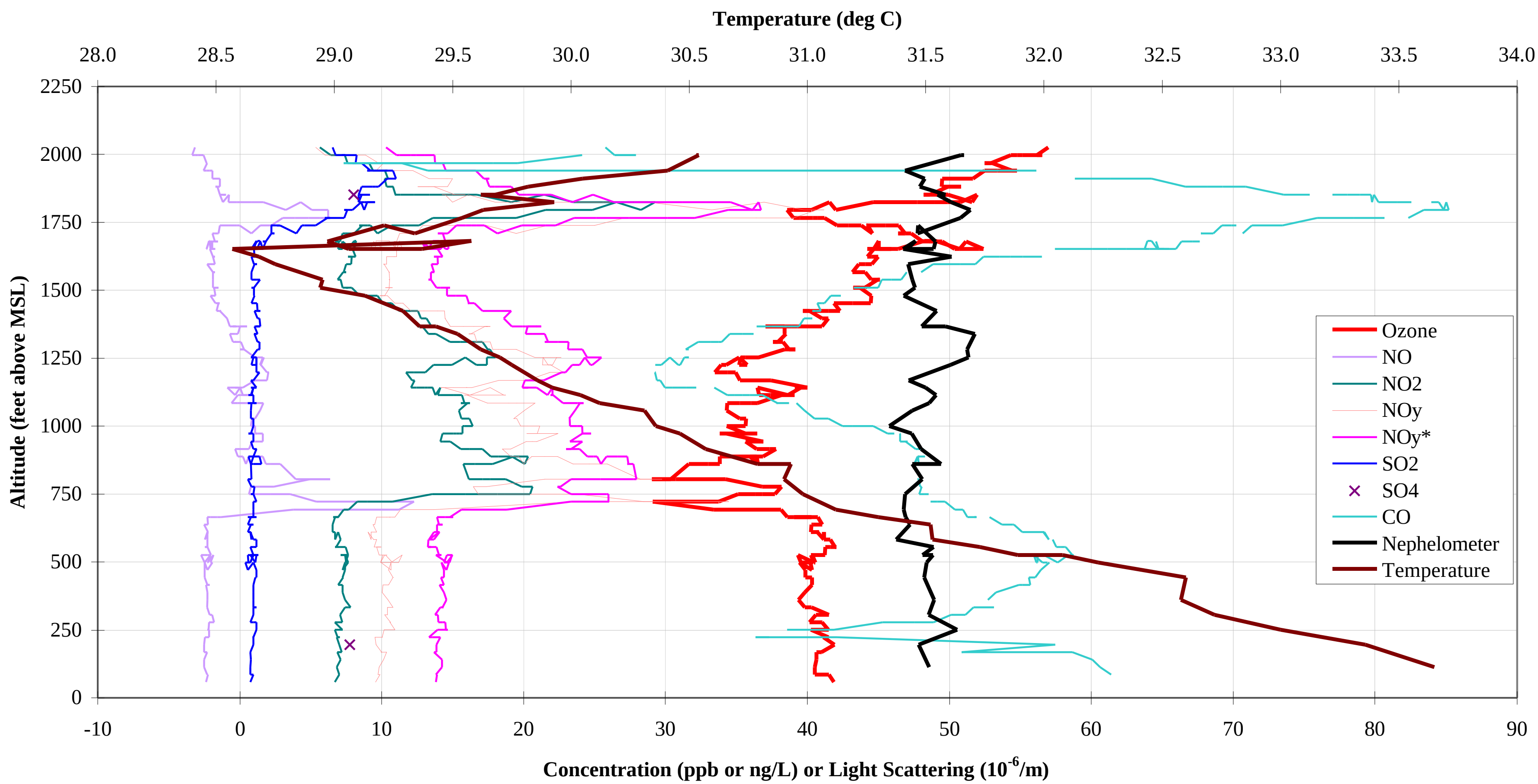


Figure 5-78. Vertical profile of air quality and temperature data collected over La Porte from 1015 to 1020 CST on September 1, 2000.

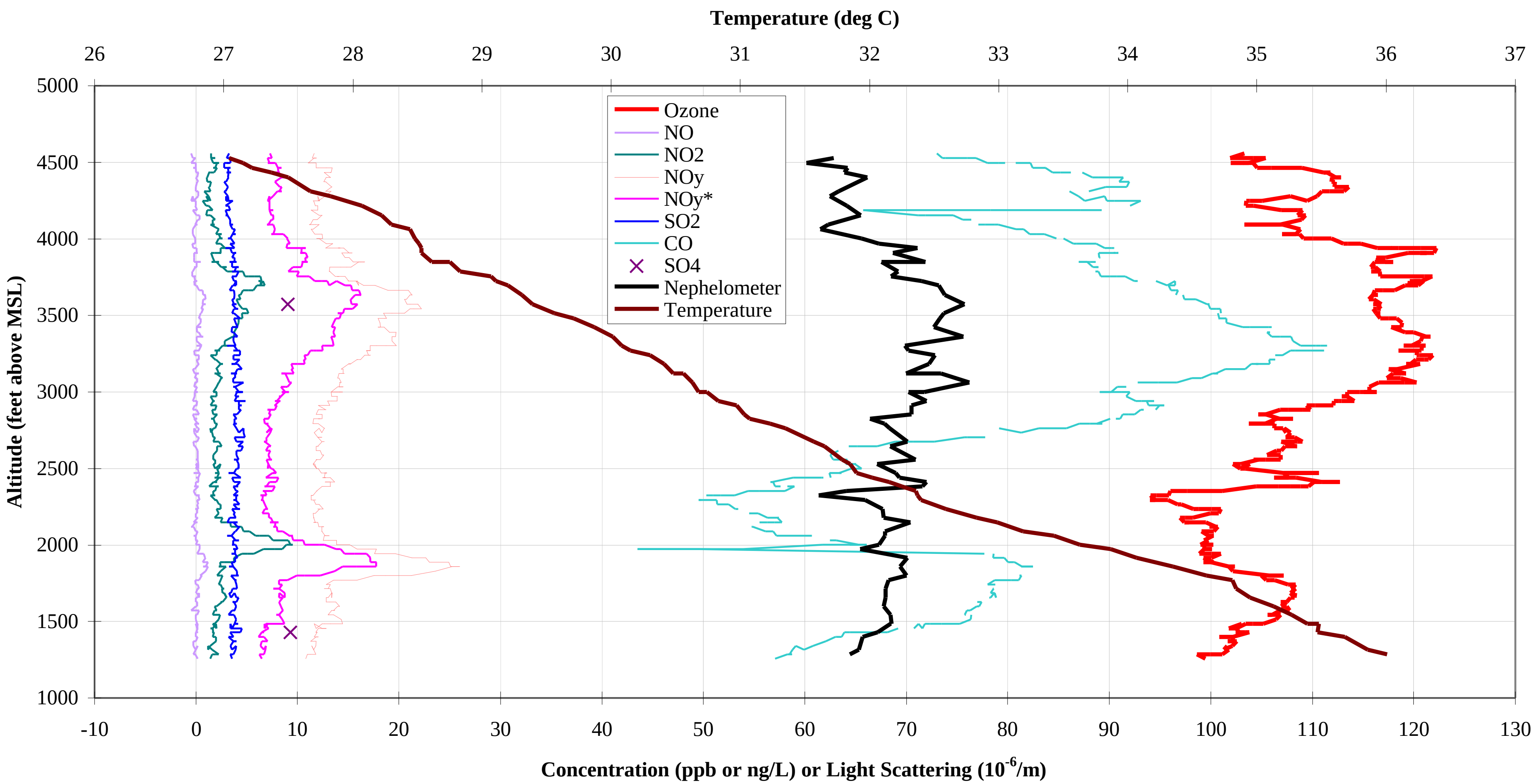


Figure 5-79. Vertical profile of air quality and temperature data collected over Galveston Bay from 1516 to 1524 CST on September 1, 2000.

5.9 FLIGHT 146, SEPTEMBER 3, 2000

On September 3, 2000, one flight began at 1002 CST and concluded at 1303 CST. Unlike previous flight patterns, the aircraft flew northeastward toward Liberty, at which point it flew south across Galveston Bay to Galveston (**Figure 5-80**). The aircraft then flew north toward, and then west parallel to, the I-10 corridor before making a box climb to 10,000 ft msl (3050 m msl) over Katy, Texas. The aircraft then turned east on I-10 and flew over the Ship Channel to Baytown. Finally, a series of northeast-southwest transects were flown over Galveston Bay, followed by a box climb over Galveston Bay to about 3500 ft msl (1067 m msl), and then a return to Ellington Field. The typical flight altitude was approximately 1500 ft msl (457 m msl).

5.9.1 Overview of Meteorology and Air Quality

The synoptic pattern over Texas, depicted in **Figure 5-81** (0600 CST on September 3, 2000), included a broad ridge of high pressure at 500 mb over the southwest and south central United States, with anticyclonic flow over Houston. At the surface, there was a high-pressure area centered around San Antonio, which created an west-east pressure gradient over Houston.

The mixing height, as estimated by profiler reflectivity data (C_n^2) at Ellington Field, was around 984 ft msl (300 m msl) overnight and during the early morning (**Figure 5-82**). Beginning around 0800 CST (1400 UTC), the mixing height increased and reached 5904 ft msl (1800 m msl) by 1600 CST (2200 UTC). At 1630 CST (2230 UTC), the mixing height rapidly increased to 8200 ft msl (2500 m msl). By 1700 CST (2300 UTC), convective activity had moved into the region (**Figure 5-83**).

Within the lowest 1000 m, the winds were moderate westerly in the morning. At around 1100 CST, the winds were light and variable in the lowest 1640 ft msl (500 m msl) shifting to light southwesterly around 1500 CST (**Figure 5-84**). Similar to conditions during the previous flight, afternoon thunderstorms cleaned out the region. When thunderstorms moved into the region at 1700 to 1800 CST, the winds observed by the Ellington Field radar wind profiler increased and mixing heights at this time were no longer apparent in the radar profiler data.

5.9.2 Spatial Characteristics of Ozone and NO_x Horizontal

Morning Horizontal

- No morning flight was performed to characterize air quality conditions.

Afternoon Horizontal

- Peak surface ozone concentrations were 127 ppb in the Baytown area at CAMS 611 at 1600 CST. Multiple sites in the Ship Channel area reported surface ozone concentrations greater than 90 ppb while concentrations above 100 ppb were observed in the Baytown and La Porte areas. Thunderstorms moved into the region around 1800 CST, at which time surface ozone levels dropped by as much as 60 to 70 ppb.

- Peak afternoon ozone concentrations observed by the aircraft were about 180 ppb and were observed at 1500 ft msl (457 m msl) over Galveston Bay, east of the Ship Channel, at 1220 CST (**Figure 5-85**). Collocated NO_y, SO_2, and NO concentrations were about 15 ppb, 5 ppb, and 0 ppb respectively. This peak was within the light westerly flow observed at Ellington Field by the radar wind profiler prior at that time (Figure 5-84).
- Ozone concentrations over downtown Houston and points west were considerably lower than those east of Houston, which was consistent with the observed westerly flow during a majority of the day.

Afternoon Vertical

- The box climb over Galveston Bay beginning at 1243 CST shows a temperature inversion at 2600 to 3000 ft msl (792 to 915 m msl) (**Figure 5-86**). Below the inversion, ozone, NO_y, NO, and SO_2 concentrations were about 160, 20, 2, and 10 ppb, respectively. Ozone concentrations above the inversion were 90 ppb with low NO_y, NO, and SO_2 concentrations. Ozone concentrations above this inversion were similar to the aloft concentrations over Katy and were associated with northerly winds. The high ozone concentrations below the inversion were associated with the westerly flow. The high ozone concentrations were probably related to both central Houston and Ship Channel area emissions.
- The box climb over Katy (**Figure 5-87**) showed only moderate ozone concentrations ranging from 60 to 90 ppb and very low NO_y, NO, and SO_2 concentrations.
  - From 1500 to 3500 ft msl (457 to 1067 m msl), ozone concentrations increased from 60 to 90 ppb.
  - There was a temperature inversion at 3500 ft msl (1067 m msl). Above this inversion to about 7000 ft msl (2134 m msl), ozone concentrations were about 90 ppb. This layer of higher ozone concentrations was associated with northerly aloft winds (Figure 5-87).

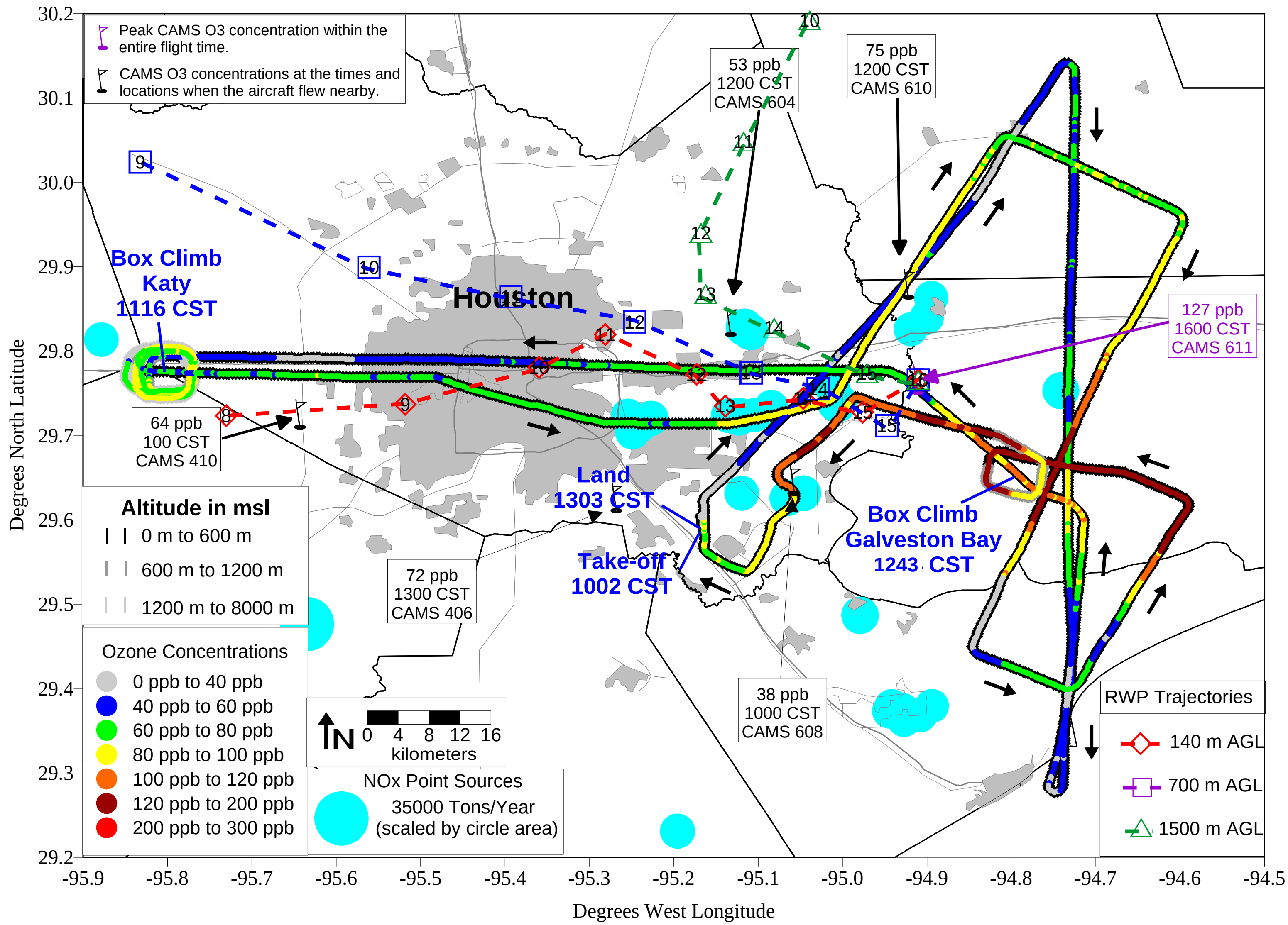


Figure 5-80. Flight 146 flight position, altitude, aloft ozone concentrations, and CAMS surface ozone concentrations during the afternoon of September 3, 2000.

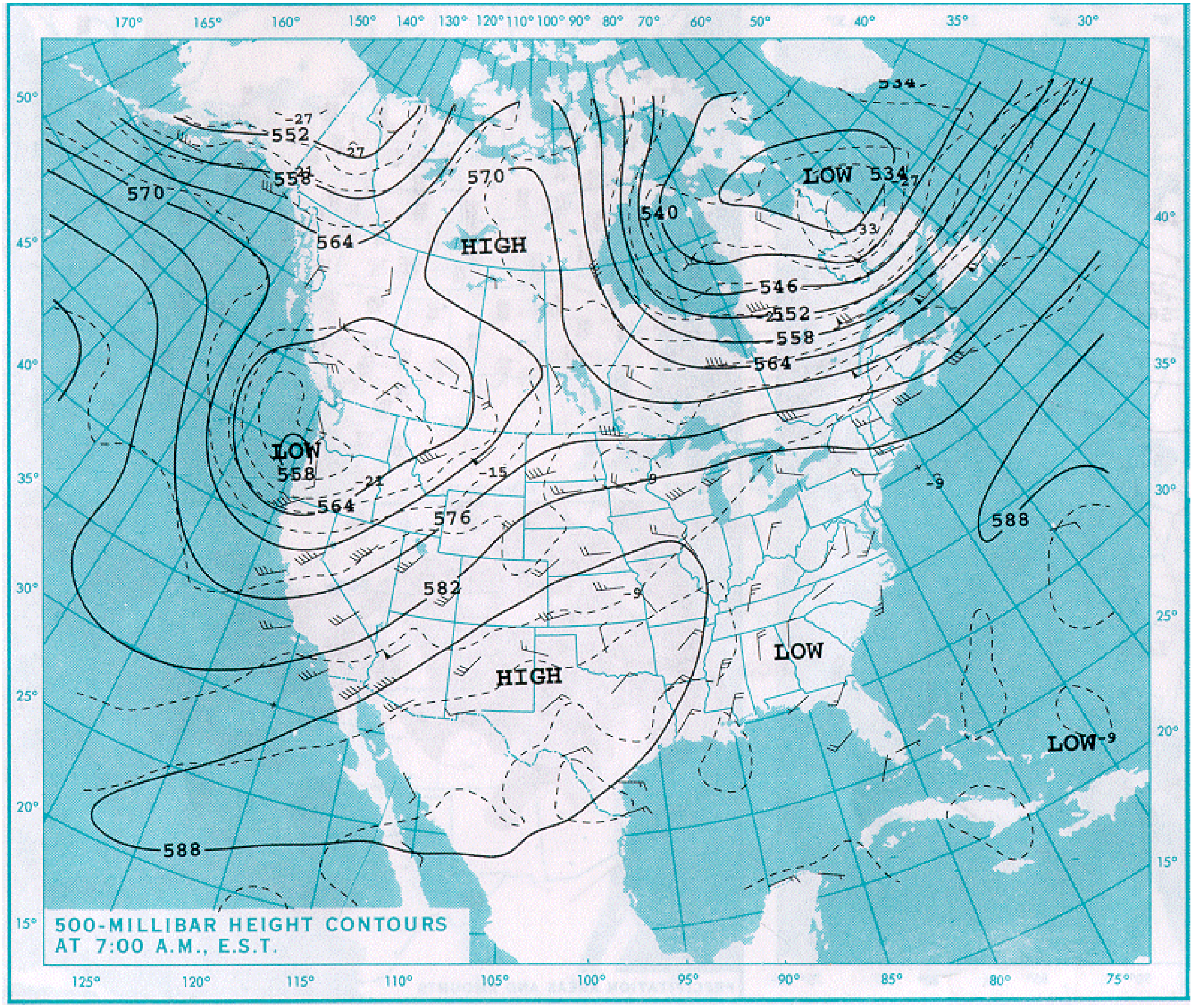


Figure 5-81. Height contours of the 500-mb pressure surface at 0600 CST on September 3, 2000.

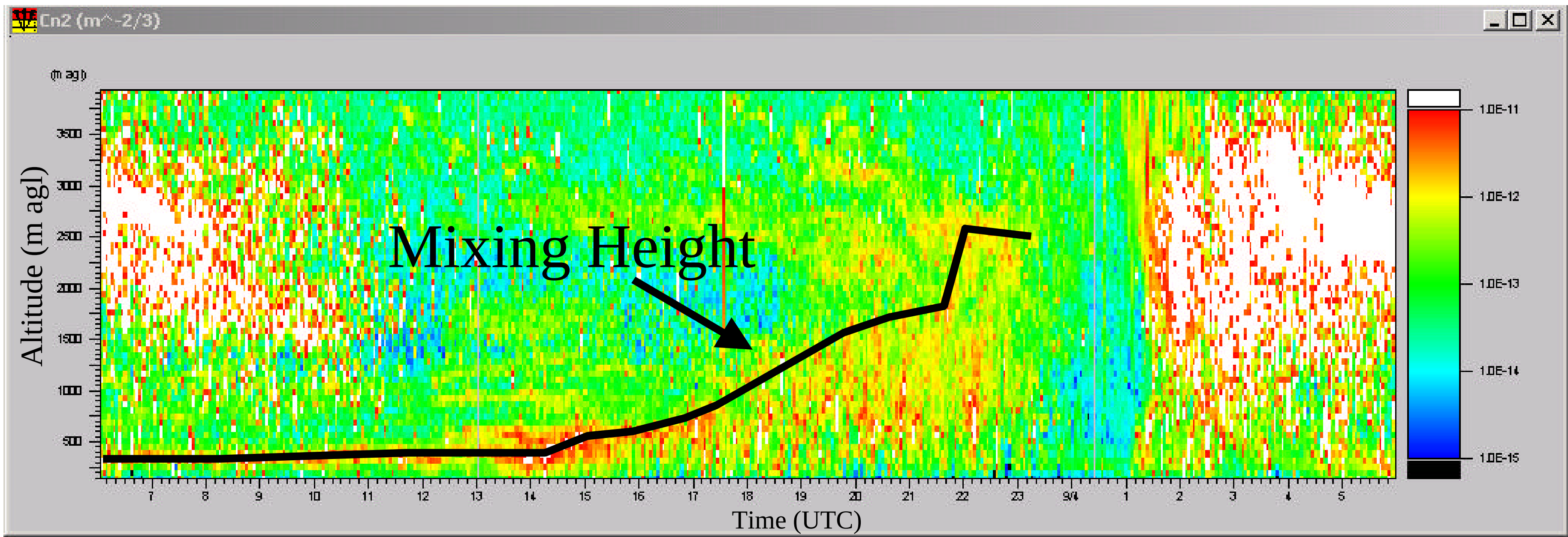


Figure 5-82. Radar wind profiler reflectivity data (C_n^2) and estimated mixing height for September 3, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

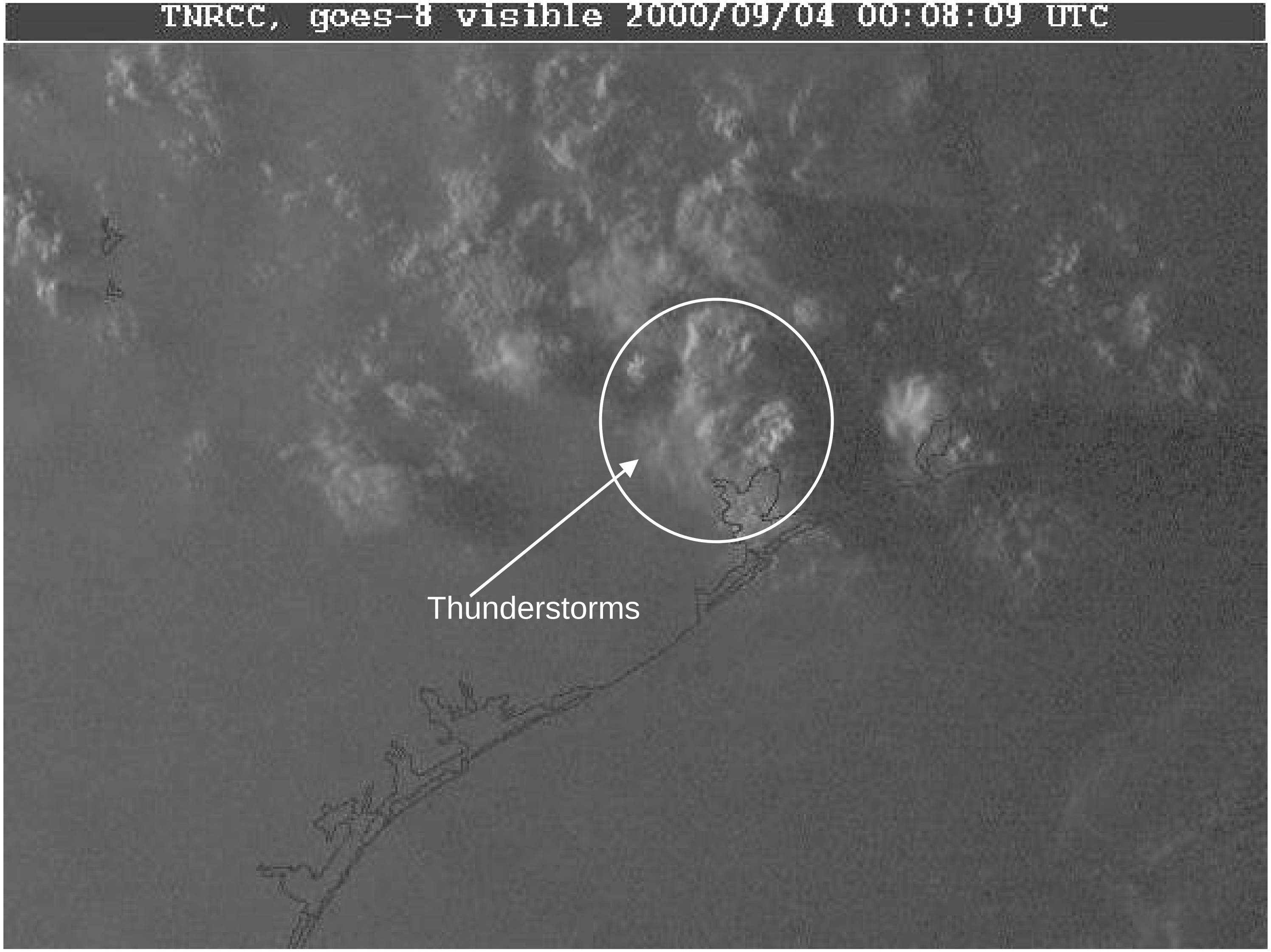


Figure 5-83. Visible satellite imagery at 1808 CST (0008 UTC) on September 3, 2000.

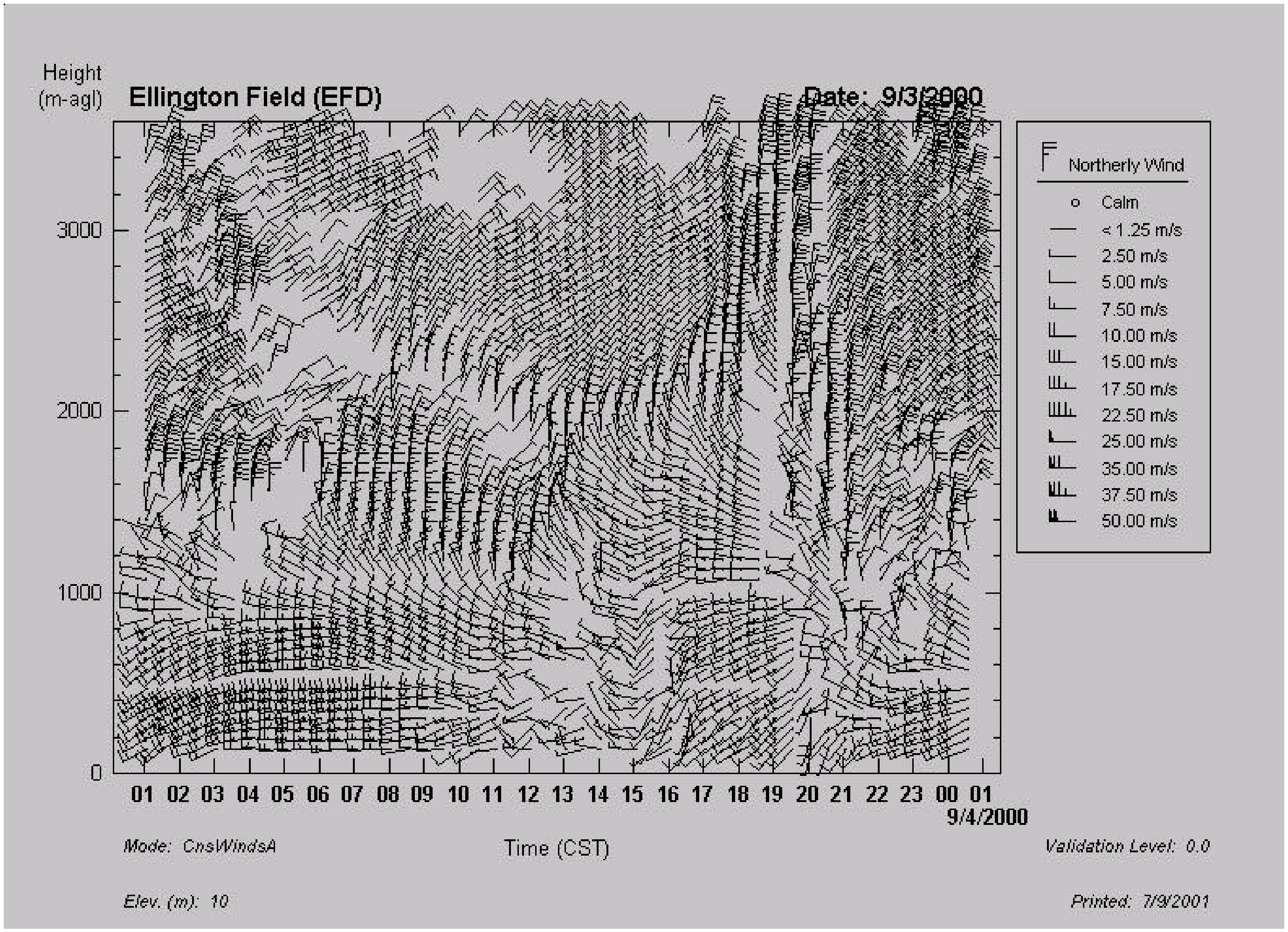


Figure 5-84. Radar wind profiler data for September 3, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

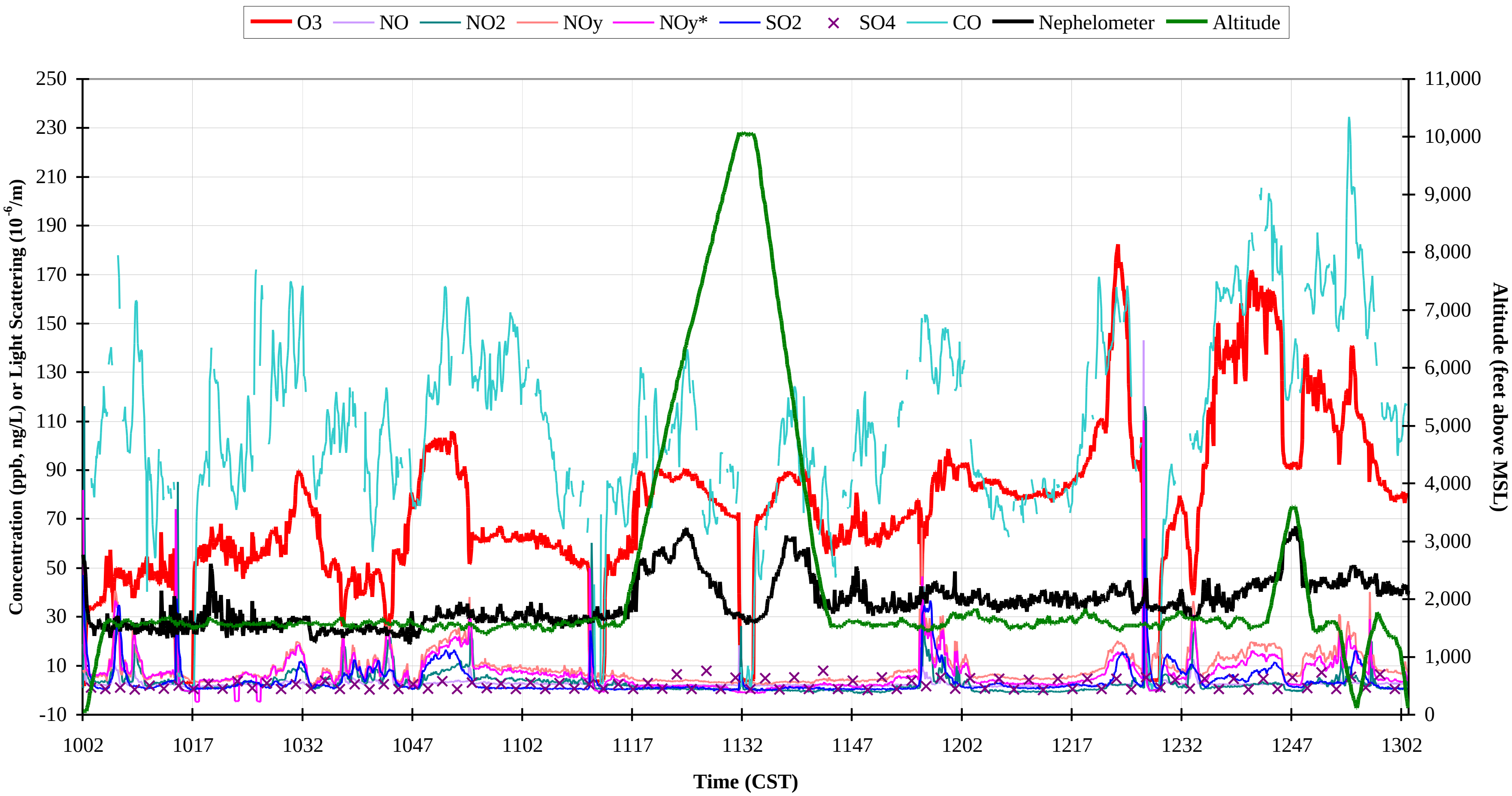


Figure 5-85. Time-series plot of air quality data from 1002 to 1302 CST on September 3, 2000.

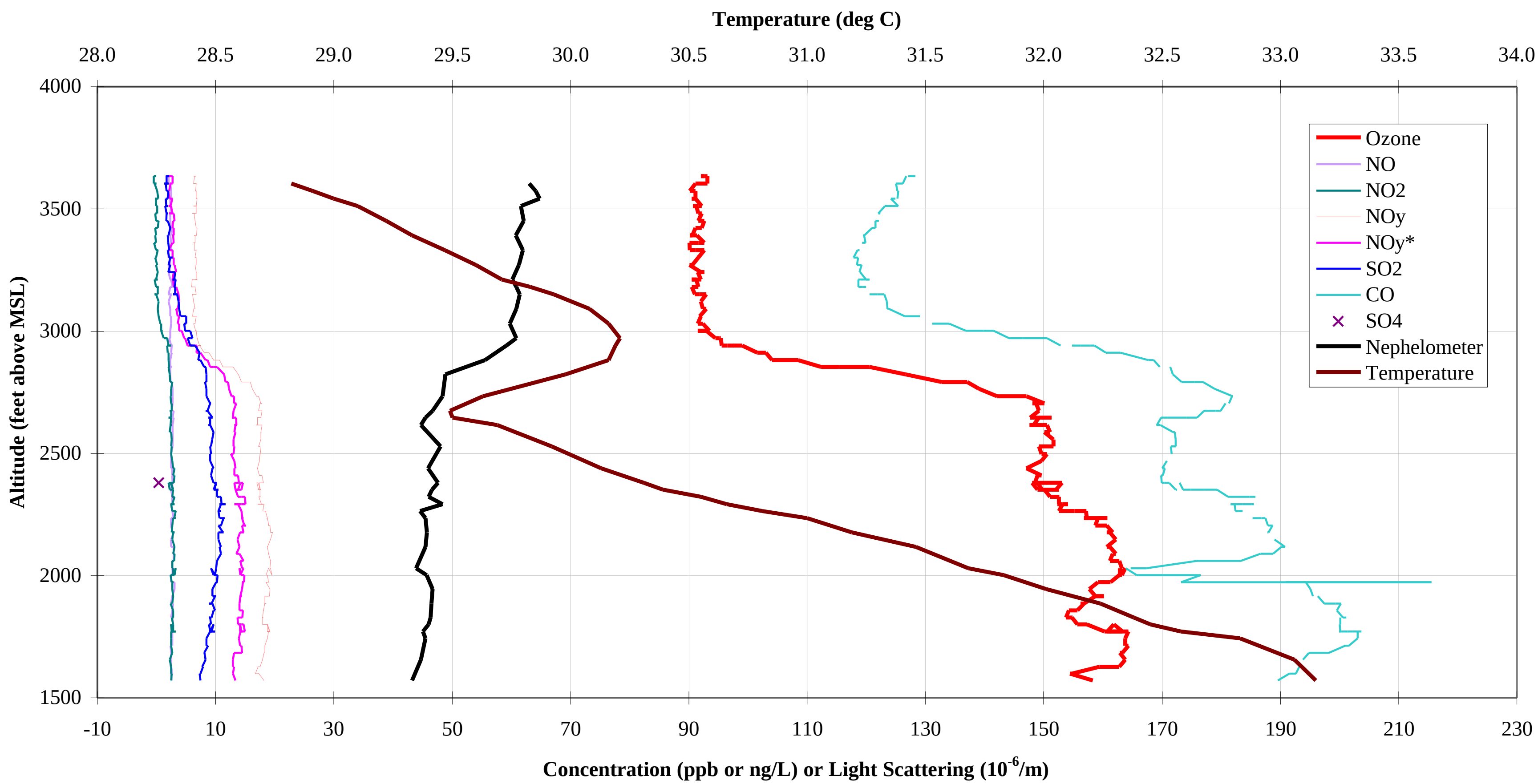


Figure 5-86. Vertical profile of air quality and temperature data collected over Galveston Bay from 1243 to 1248 CST on September 3, 2000.

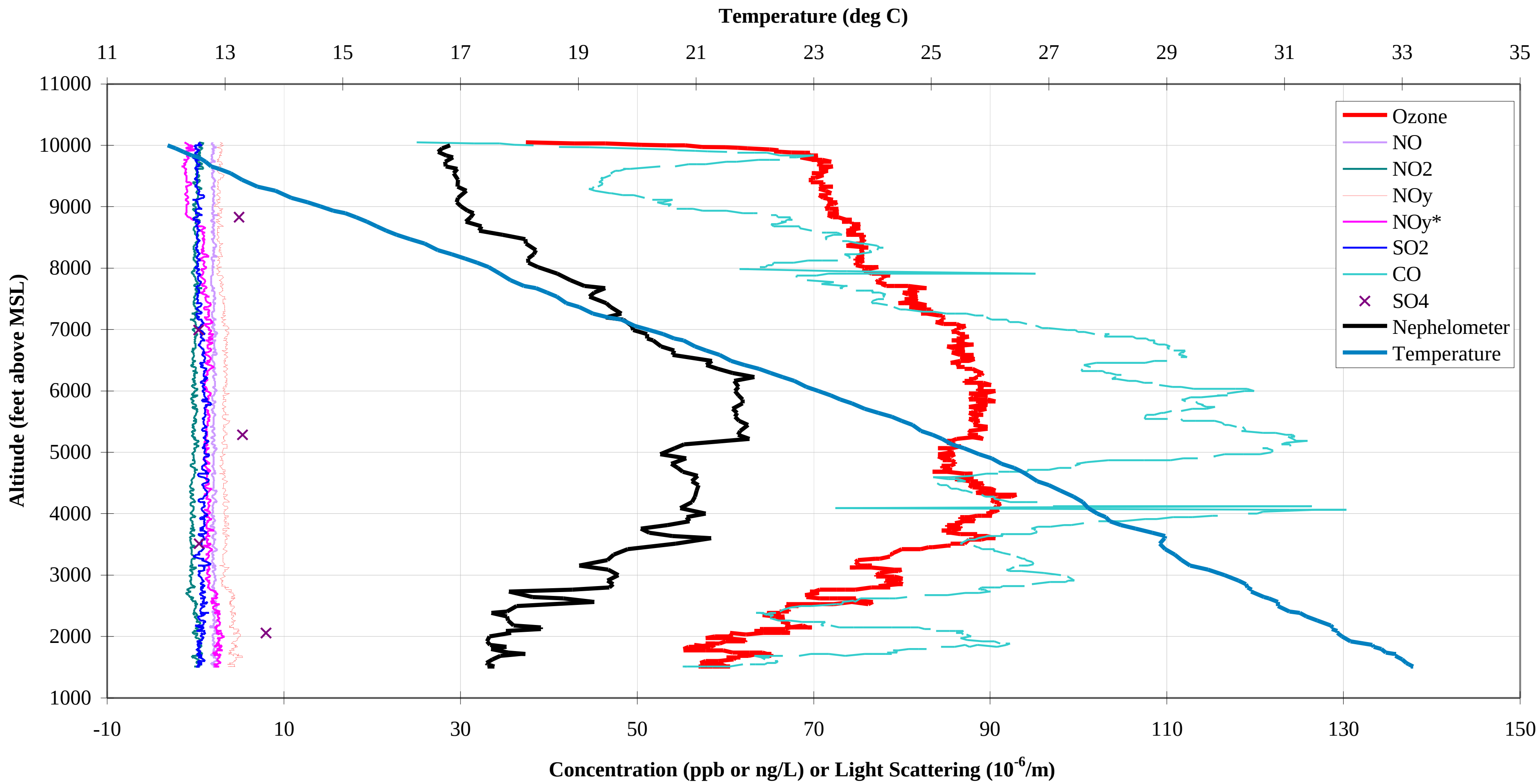


Figure 5-87. Vertical profile of air quality and temperature data collected over Katy, Texas, from 1115 to 1145 CST on September 3, 2000.

5.10 FLIGHT 147A AND 147B, SEPTEMBER 4, 2000

On September 4, 2000, there was a late morning/early afternoon flight and a late afternoon flight. For the late morning flight, the aircraft took off from Ellington Field and flew a segment towards north of Beaumont, followed by a box climb up to 10,000 ft msl (3050 m msl) over Deweyville, Texas, and then two traverses each at stepped levels of 1000, 2000, and 3000 ft msl (305, 610, and 915 m msl) (**Figure 5-88**). The aircraft landed at Southeast Texas Regional Airport near Port Arthur. The pattern of the afternoon flight was similar to that of the morning flight (**Figure 5-89**) in reverse. Three segments were flown over the Beaumont–Port Arthur region. Two of these segments were flown in a step pattern at 1000, 2000, and 3000 ft msl (305, 610, and 915 m msl). The third segment was flown only at 1000 and 2000 ft msl (305 and 610 m msl). The aircraft then returned to Ellington Field. These flight patterns were not flown on any other days that were analyzed.

5.10.1 Overview of Meteorology and Air Quality

Figure 5-90 shows the synoptic pattern over Texas, which included a ridge of high pressure at 500 mb centered over Texas with anticyclonic flow. Locally, the EDAS back-trajectories at 140 m agl showed very short transport distances from the northwest from 0900 to 1500 CST (the time of the peak afternoon ozone concentrations). The air at this level originated over Louisiana 24 hours earlier (**Figure 5-91**). Surface wind observations indicate a late afternoon Gulf Breeze, which is not captured in the 140-m msl back-trajectory. Air at 700 and 1500 m agl originated in Mississippi and Arkansas, respectively (Figure 5-91).

Visible satellite imagery revealed smoke layers throughout the region from marsh fires that may have affected ozone concentrations in Houston. However, the onset of northeasterly winds during the early afternoon hours blew much of the smoke away from the Beaumont–Port Arthur area.

Since the flight path was confined to the Beaumont–Port Arthur area, the radar profiler data from Ellington Field was not utilized for this day, and data from the Jefferson County radar profiler was not readily available.

High surface and aloft ozone concentrations occurred in the vicinity of Beaumont, Jefferson County Airport, Port Arthur, and Sabine, Texas. The highest surface ozone concentration was 115 ppb at CAMS 28 at 1600 CST near Port Arthur. Four CAMS sites reported ozone concentrations of 100 ppb or higher, all located in a line extending from Sabine to Beaumont.

5.10.2 Spatial Observations of Ozone and NO_x

Morning Horizontal

- During the early morning hours, surface ozone concentrations were titrated at all sites, with concentrations ranging from near 0 to 20 ppb. Morning NO_x concentrations ranged from 9 ppb at CAMS 640 (near Sabine) to about 25 ppb at CAMS 64 (near Hamshire).

These morning NO_x concentrations are much lower than morning NO_x concentrations on other flight days in the Houston area.

- The aircraft flew too late in the morning to determine aloft background ozone concentrations.

Late Morning and Afternoon Horizontal

- Surface ozone concentrations peaked along a line from Sabine to Beaumont. Ozone concentrations peaked earliest at Sabine, about 1400 CST, and latest at Beaumont, about 1700 CST. These peaks were consistent with the late afternoon Gulf Breeze observed at CAMS sites.

Afternoon Vertical

- During the late morning and early afternoon hours, the box climb over Deweyville beginning at 1153 CST showed ozone concentrations of about 55 ppb from 1200 ft msl (366 m msl) (the start of the box climb) to approximately 2000 ft msl (610 m msl), with NO_y concentrations around 2 to 3 ppb, and NO and SO_2 concentrations near 0 ppb throughout the entire layer (**Figure 5-92**).

- Ozone concentrations observed by the aircraft were generally around 80 to 90 ppb south and west of the Port Arthur–Beaumont area during the afternoon hours. The aircraft's descent in the afternoon from the first traverse south of Port Arthur revealed ozone concentrations of 85 to 90 ppb from 1000 to 3000 ft msl (305 to 915 m msl) at 1630 CST (**Figure 5-93**). NO_y, SO_2, and NO concentrations were 10, 5, and 0 ppb, respectively. However, at about 1000 ft msl (305 m msl), ozone concentrations of 110 ppb, were observed just to the east of Port Arthur during the ascent from takeoff.

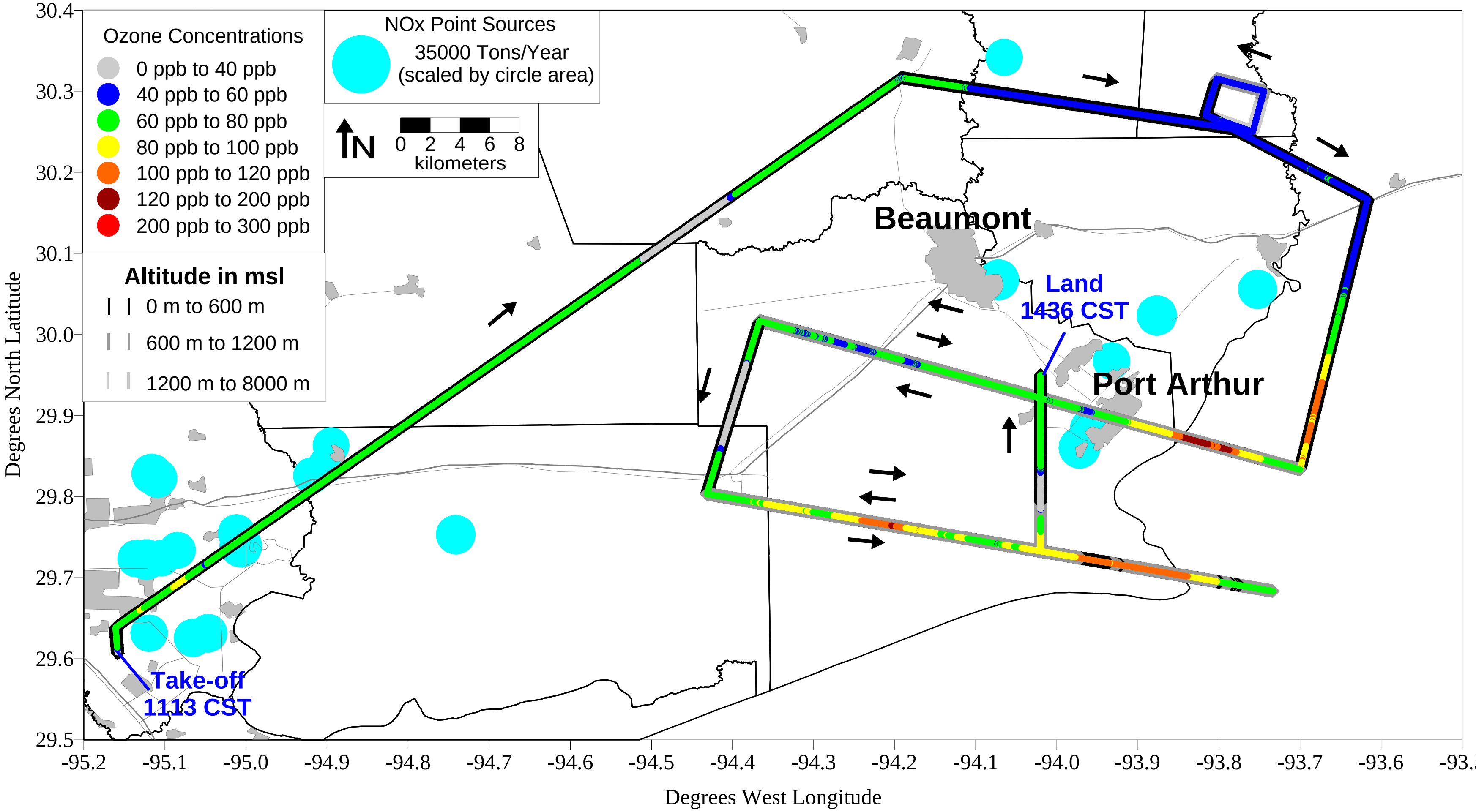


Figure 5-88. Flight 147 flight position, altitude, aloft ozone concentrations, and CAMS surface ozone concentrations during the morning of September 4, 2000.

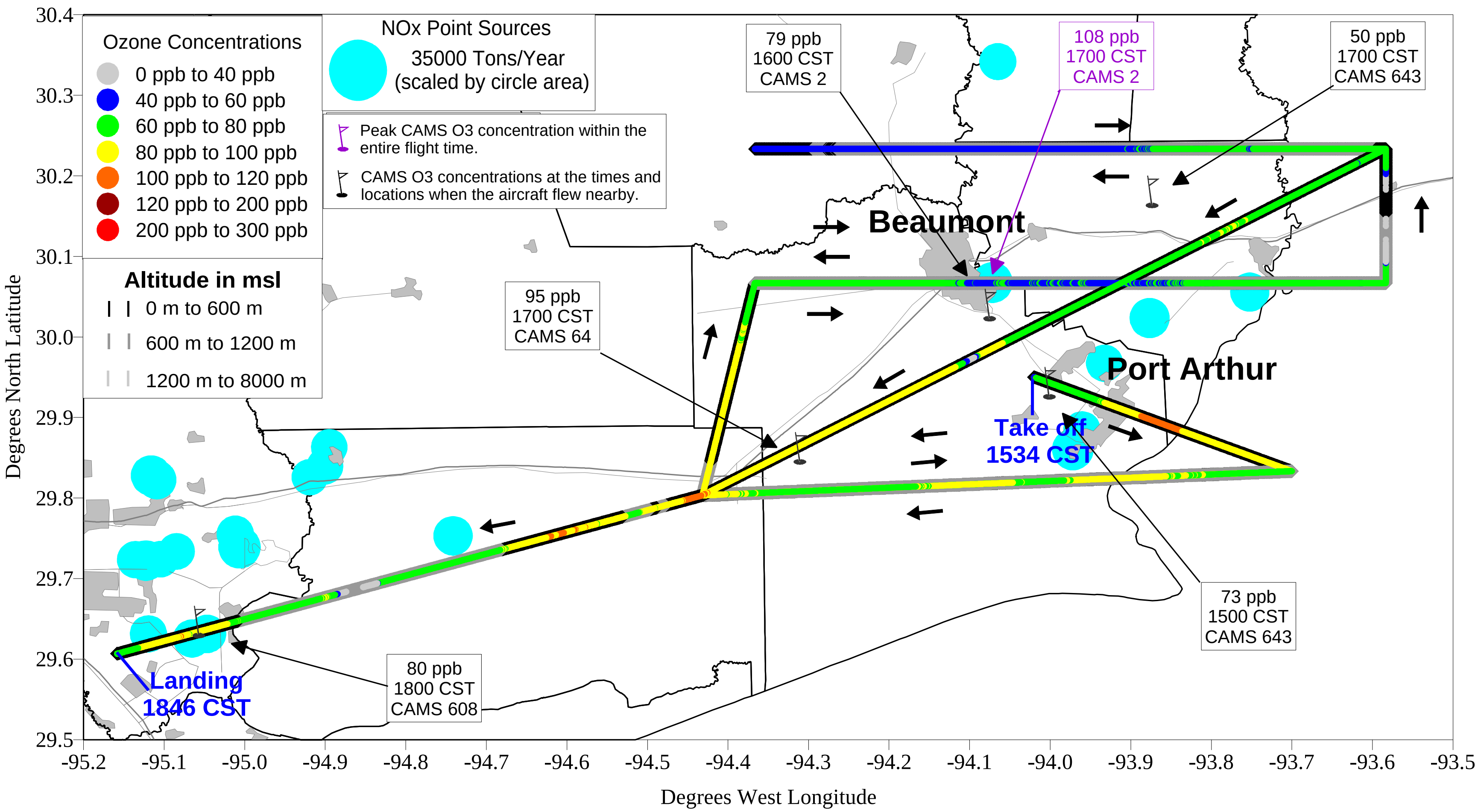


Figure 5-89. Flight 147 flight position, altitude, aloft ozone concentrations, CAMS surface ozone concentrations, and back-trajectories during the afternoon of September 4, 2000.

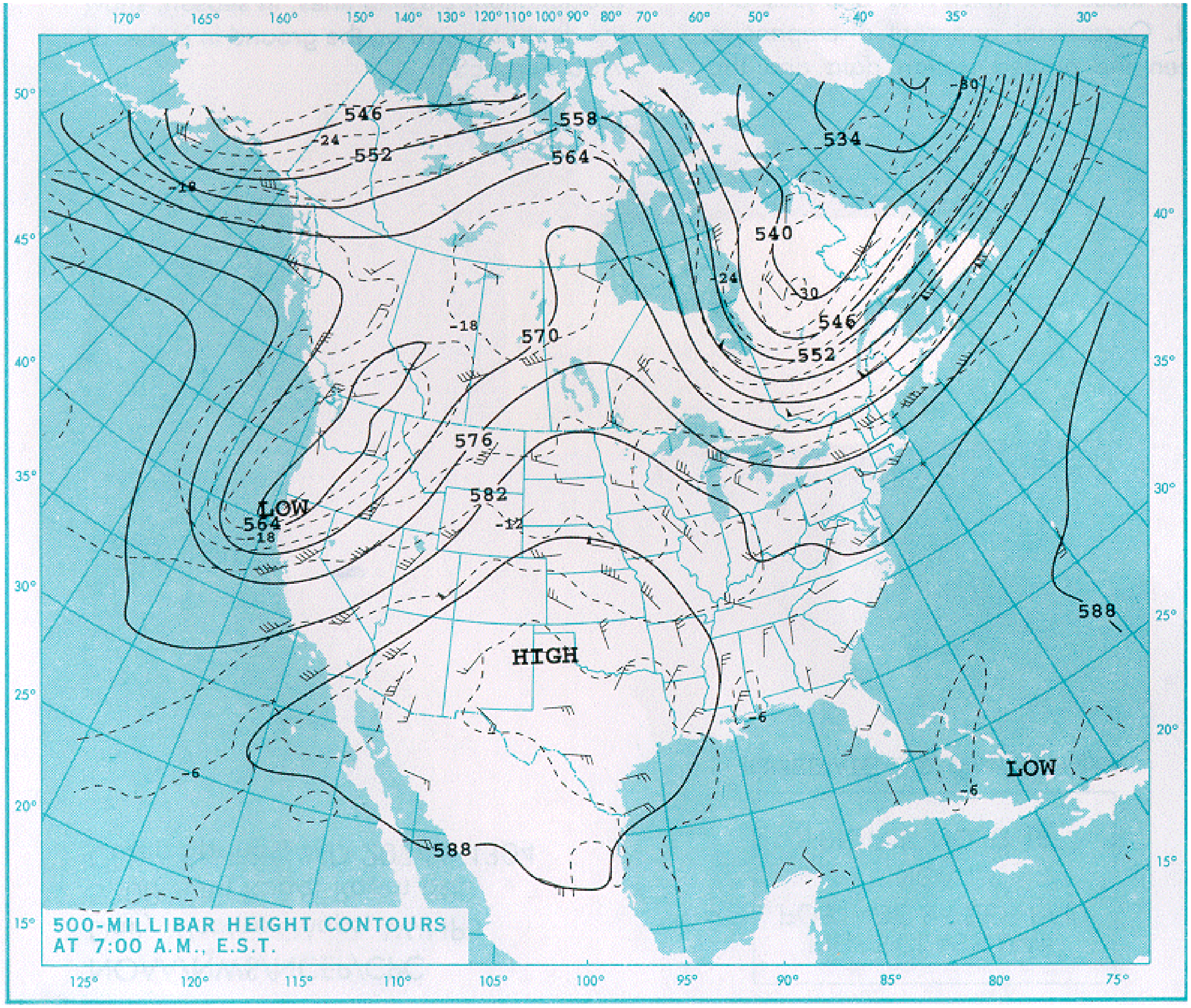


Figure 5-90. Height contours of the 500-mb pressure surface at 0600 CST on September 4, 2000.

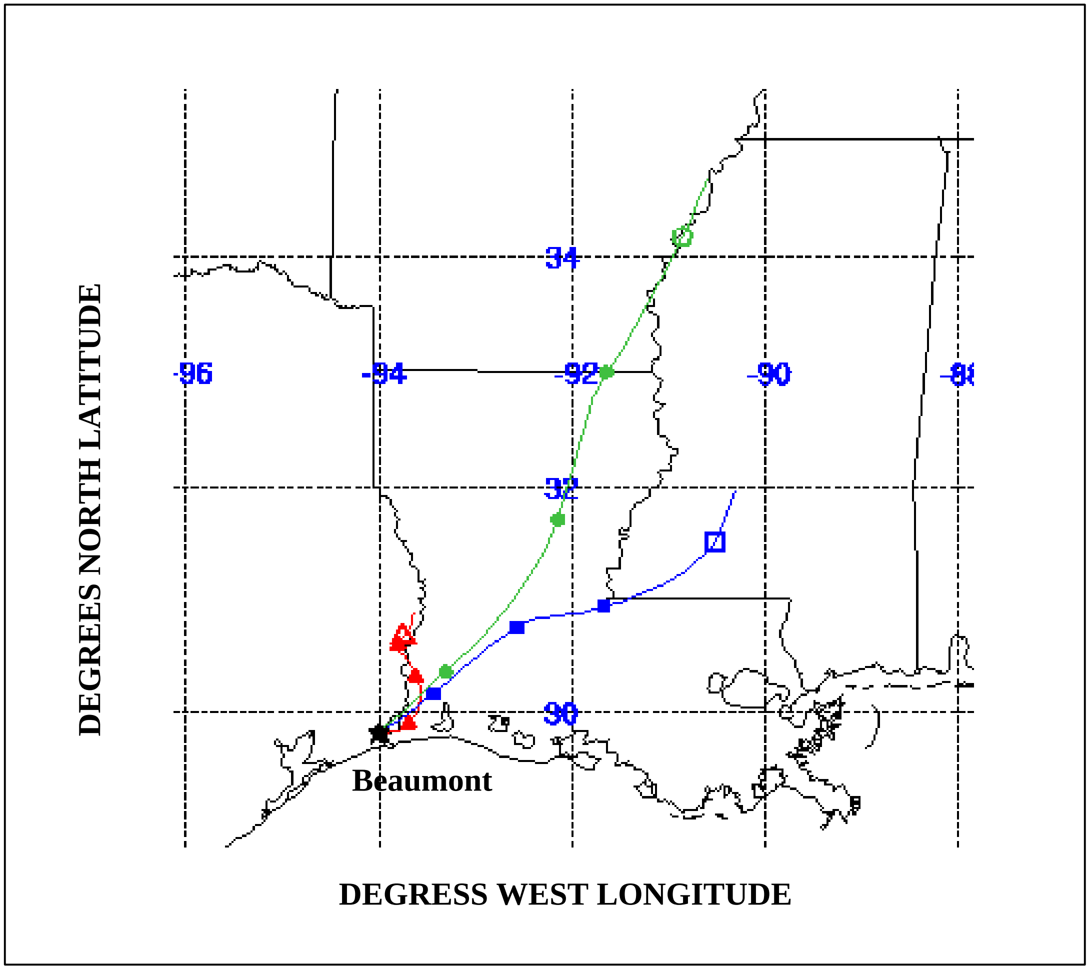


Figure 5-91. Twenty-four-hour back-trajectories for 140 m agl (red line), 700 m agl (blue line), and 1500 m agl (green line) from the general flight area in Beaumont on September 4, 2000, at 1500 CST.

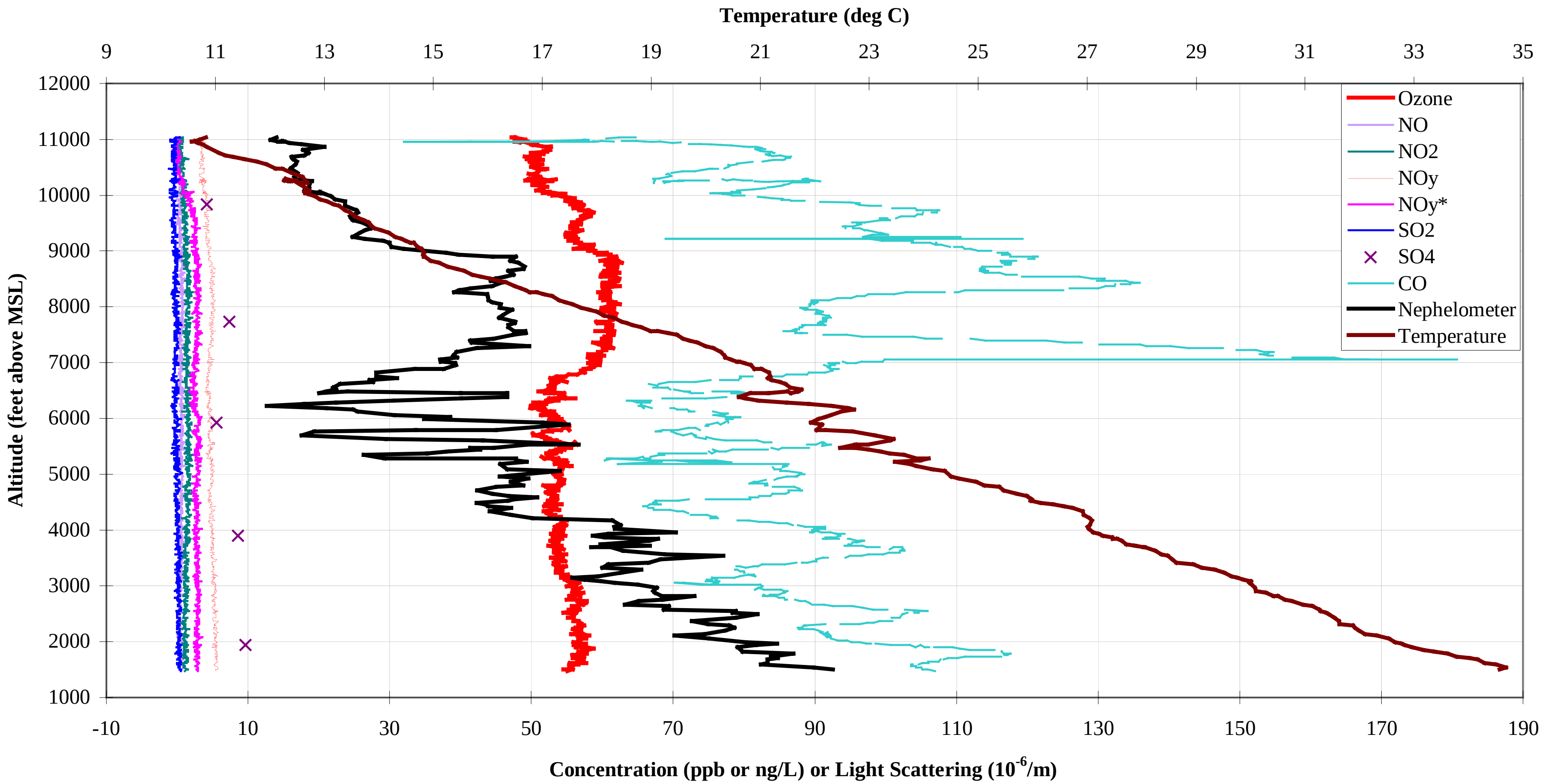


Figure 5-92. Vertical profile of air quality and temperature data collected over Deweyville, Texas, from 1153 to 1215 CST on September 4, 2000.

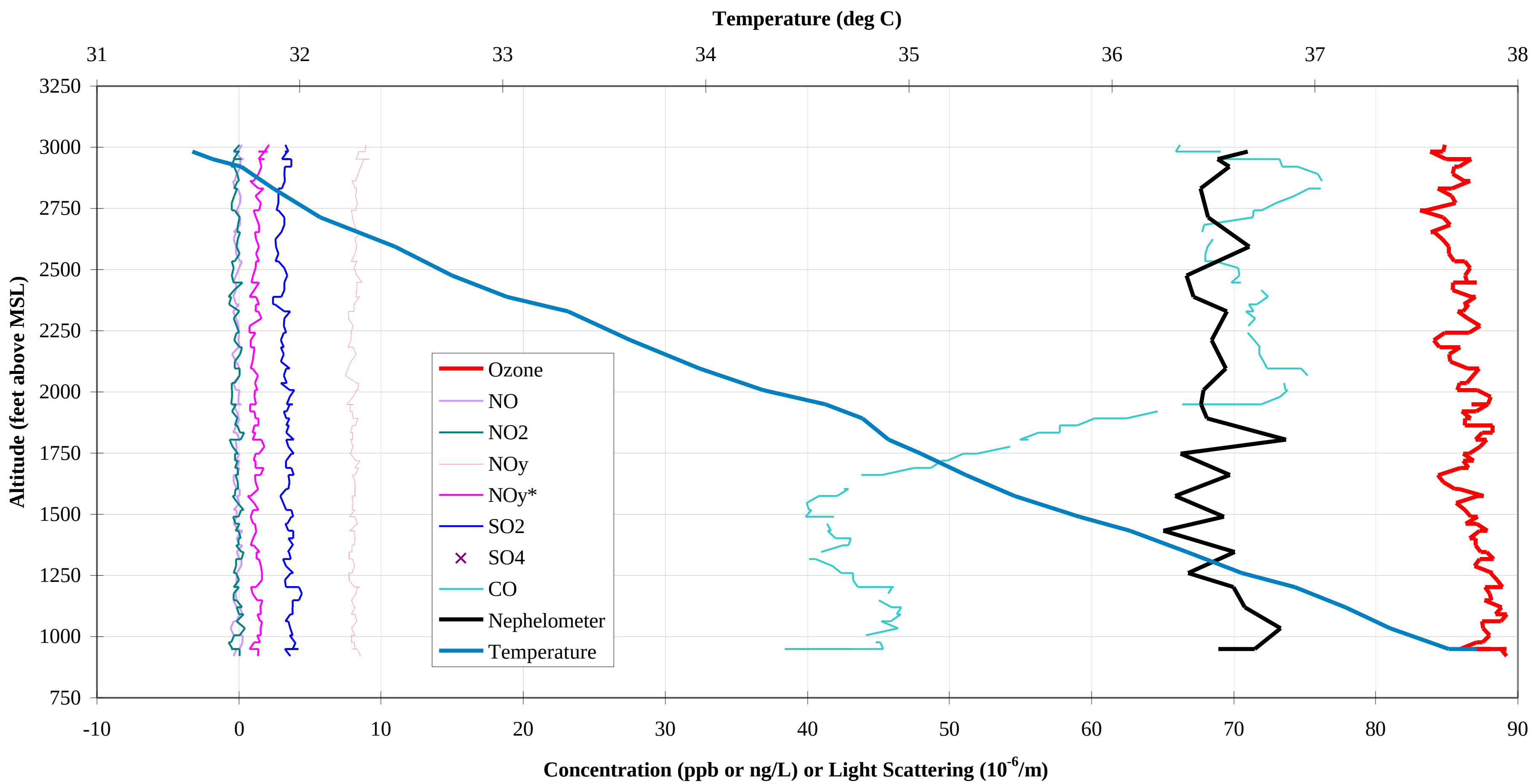


Figure 5-93. Vertical profile of air quality and temperature data collected south of Port Arthur, Texas, from 1630 to 1633 CST on September 4, 2000.

5.11 FLIGHT 148, SEPTEMBER 5, 2000

On September 5, 2000, the single afternoon flight started with a segment over La Porte, continued with a segment over Baytown, and then a segment over central Houston (**Figure 5-94**). The aircraft then flew south and then east over Trinity Bay before flying west and then east toward the coastline to Galveston. The aircraft landed in Galveston prior to the passage of widespread thunderstorm activity. The typical flight altitude was about 1500 ft msl (457 m msl), and no box climbs were flown. This flight path was not flown on any other flight days examined. Only two vertical profiles were collected during this flight, one on takeoff and one on landing.

5.11.1 Overview of Meteorology and Air Quality

The synoptic pattern over Houston, shown in **Figure 5-95a** (0600 CST on September 5) included a ridge of high pressure at 500 mb centered over the Texas panhandle. At the surface (**Figure 5-95b**), a trough of low pressure extended from the Oklahoma panhandle south to Corpus Christi, Texas.

Figure 5-96 shows that the mixing height estimated by profiler reflectivity data (C_n^2) at Ellington Field was about 328 ft msl (100 m msl) at approximately 1000 CST (1600 UTC). After 1000 CST, the mixing height increased from 328 to 12,136 ft msl (100 to 3700 m msl) by approximately 1530 CST (2130 UTC). Convection, as observed by the visible satellite imagery, moved over the region between 1430 and 1530 CST (2030 and 2130 UTC) (**Figure 5-97**); this observation agrees with a rapid rise in mixing heights at 1530 CST (2130 UTC).

As shown in **Figure 5-98**, within the lowest 500 m msl, the winds were westerly in the early morning, turning to light northerly from 0730 to 1000 CST. At 1200 CST, the winds shifted to northeasterly, at which time the mixing heights were observed to have increased rapidly. The wind pattern on this day was not similar to those on other flight days. The EDAS 140-m agl 24-hour back-trajectories showed that air arriving in the Houston area at 1600 CST originated just northeast of Houston (**Figure 5-99**). The 700- and 1500-m msl back-trajectories originated northwest of Houston, passing over Louisiana before arriving in Houston at 1600 CST.

Peak surface ozone concentrations were 185 ppb and occurred at 1400 CST at CAMS 11 at Clute, south of Houston, which is consistant with the afternoon northerly winds. High ozone concentrations were observed by the aircraft throughout central and southern Houston to the Gulf Coast (Figure 5-94).

5.11.2 Spatial Characteristics of Ozone and NO_x Horizontal

Morning Horizontal

- There was no morning flight to assess aloft morning ozone concentrations.
- The highest surface NO_y concentration was 240 ppb at 0500 CST at CAMS 01 located in central Houston. Morning NO_x concentrations above 100 ppb were observed at many downtown sites and sites in the area of the Ship Channel.

Afternoon Horizontal

- High ozone concentrations between 100 and 190 ppb were observed throughout most of the flight.
- Peak aloft afternoon ozone concentrations were about 190 ppb, observed at 1500 ft msl (457 m msl) near CAMS 11 just north of Clute at 1517 CST. This aloft ozone peak was associated with a layer of NO_y (about 30 ppb) and SO_2 (about 10 ppb) at 1523 CST (**Figure 5-100**). In addition, this peak was collocated with the maximum observed surface ozone concentration of 185 ppb at CAMS 11 at 1400 CST.
- Peak surface ozone concentrations within the Houston area were 130 ppb at CAMS 603 near the Ship Channel at 1400 CST. A majority of the sites had peak ozone concentrations over 100 ppb at either 1300 or 1400 CST.
- Aloft ozone concentrations were generally similar to surface ozone concentrations. For example, at 1440 CST at 1500 ft msl (457 m msl), ozone concentrations were observed at 110 ppb over Missouri City near CAMS 409. At CAMS 409 at 1400 CST, ozone concentrations were 110 ppb.
- The consistency between the 1500 ft msl (457 m msl) ozone concentrations and the surface ozone concentrations throughout the flight, and in the above example, suggests that the atmosphere was well-mixed to at least 1500 ft msl (457 m msl) during the afternoon. This observation is consistent with the radar profiler mixing heights during the flight.

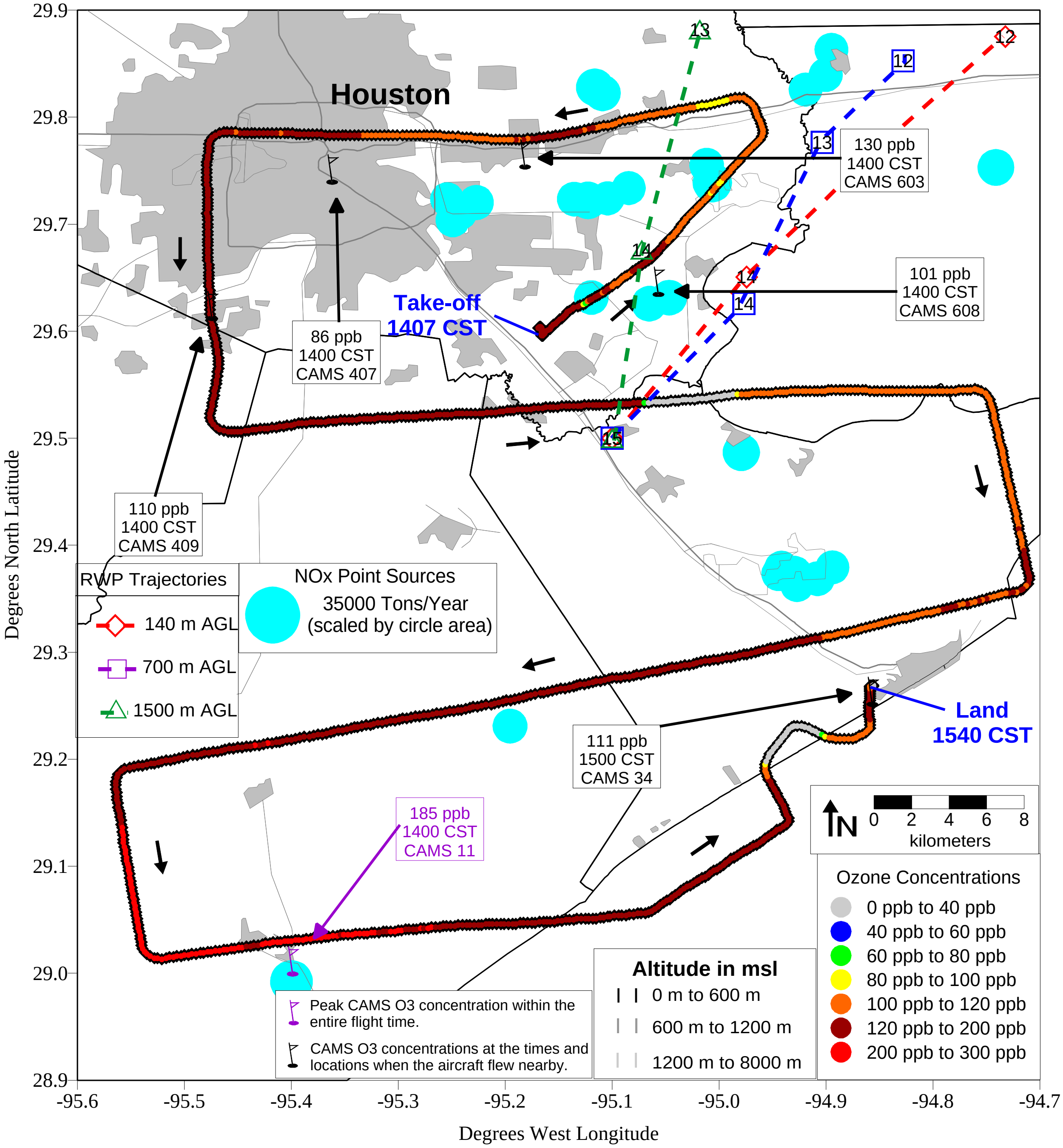


Figure 5-94. Flight 148 flight position, altitude, aloft ozone concentrations, CAMS surface ozone concentrations, and back-trajectories on the afternoon of September 5, 2000.

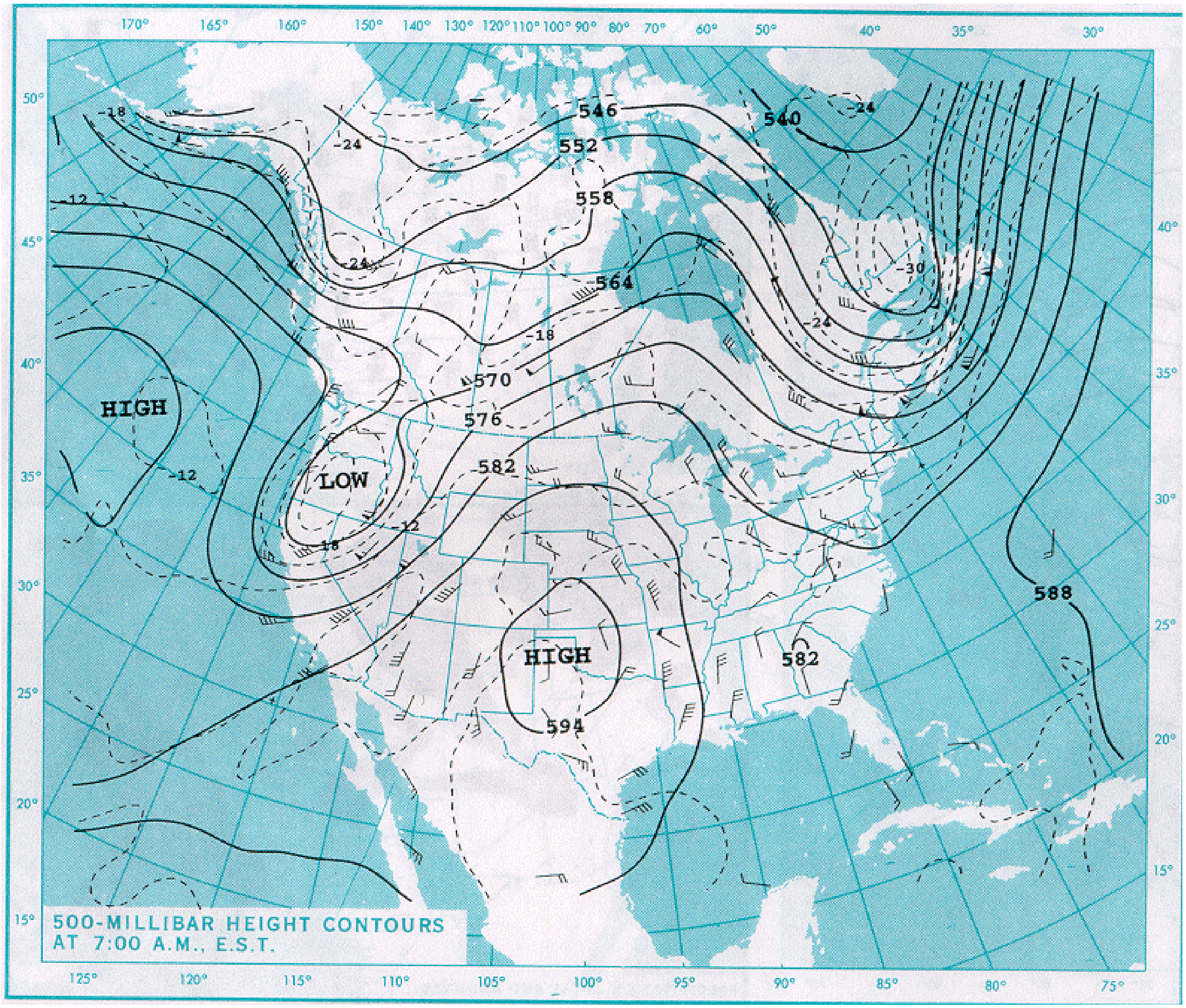


Figure 5-95a. Height contours of the 500-mb pressure surface at 0600 CST on September 5, 2000.

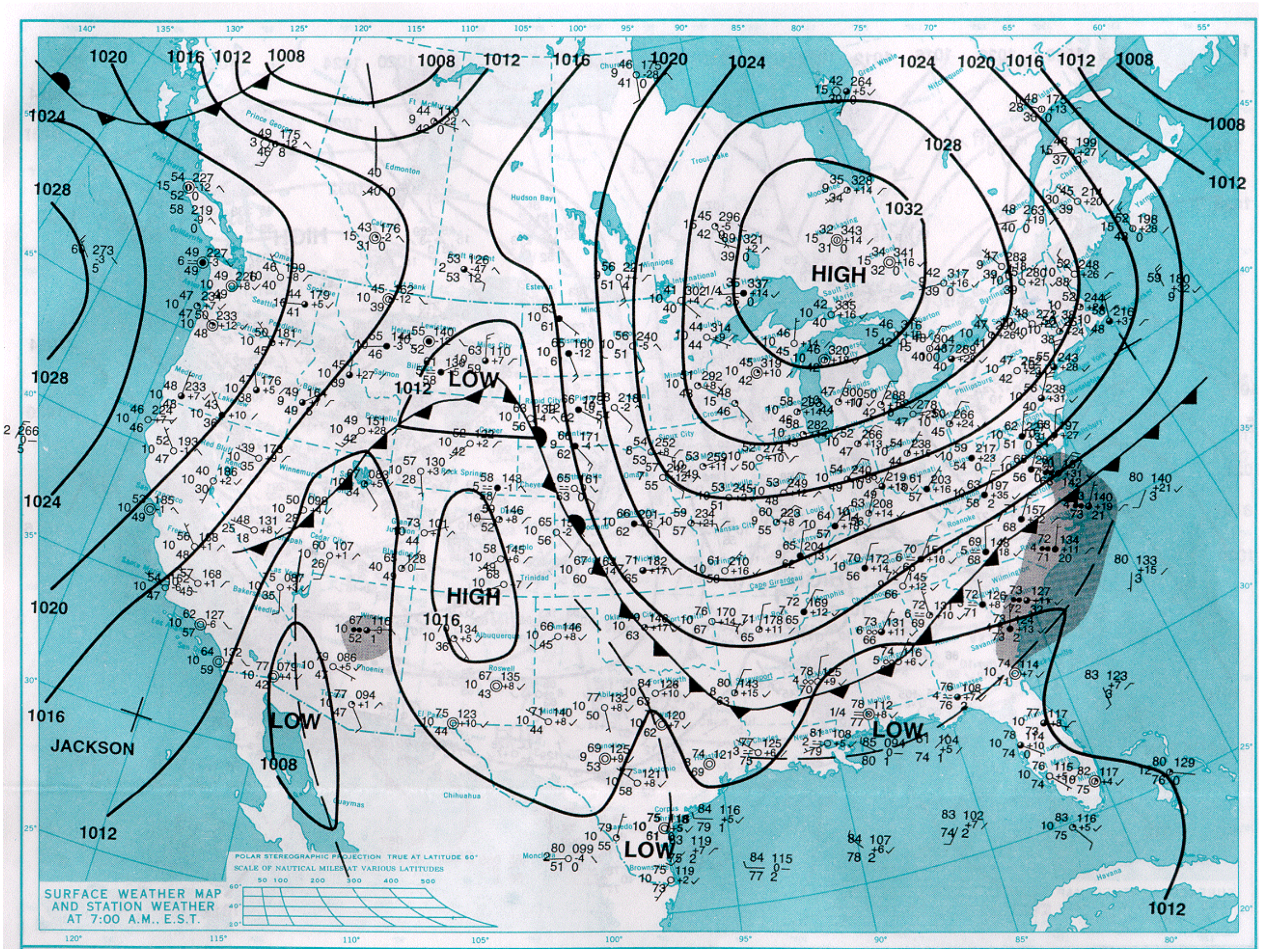


Figure 5-95b. Surface analysis at 0600 CST on September 5, 2000.

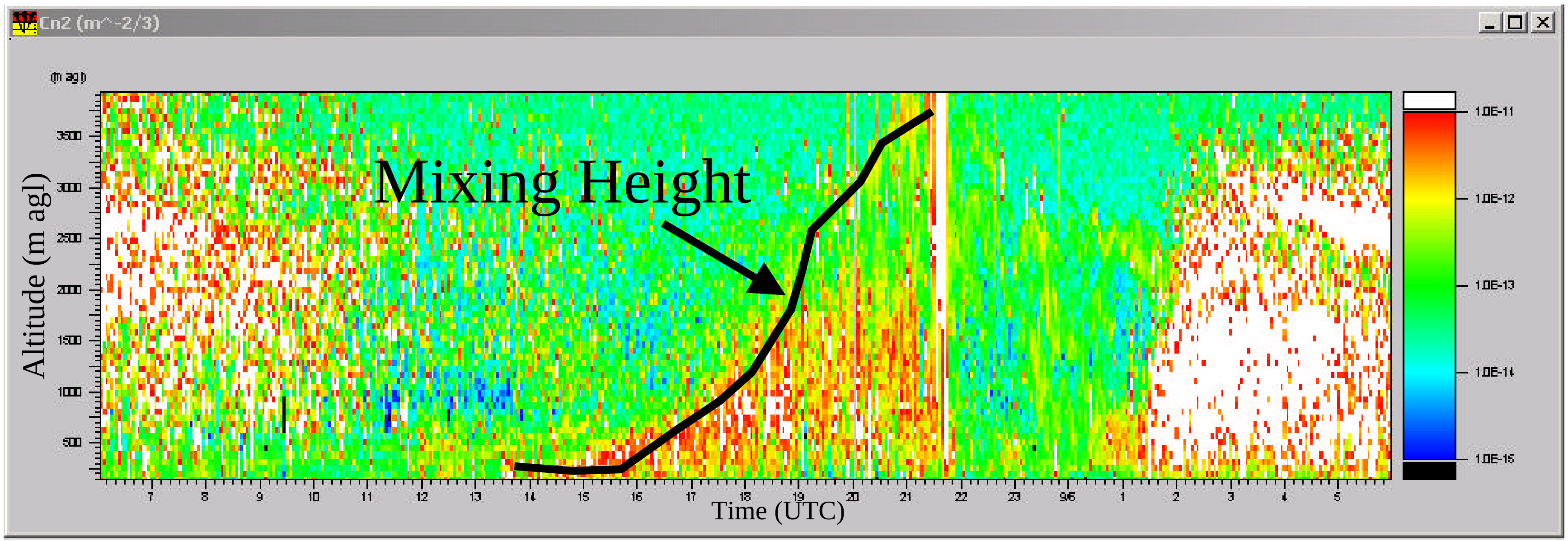


Figure 5-96. Radar wind profiler reflectivity data (C_n^2) and estimated mixing height for September 5, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

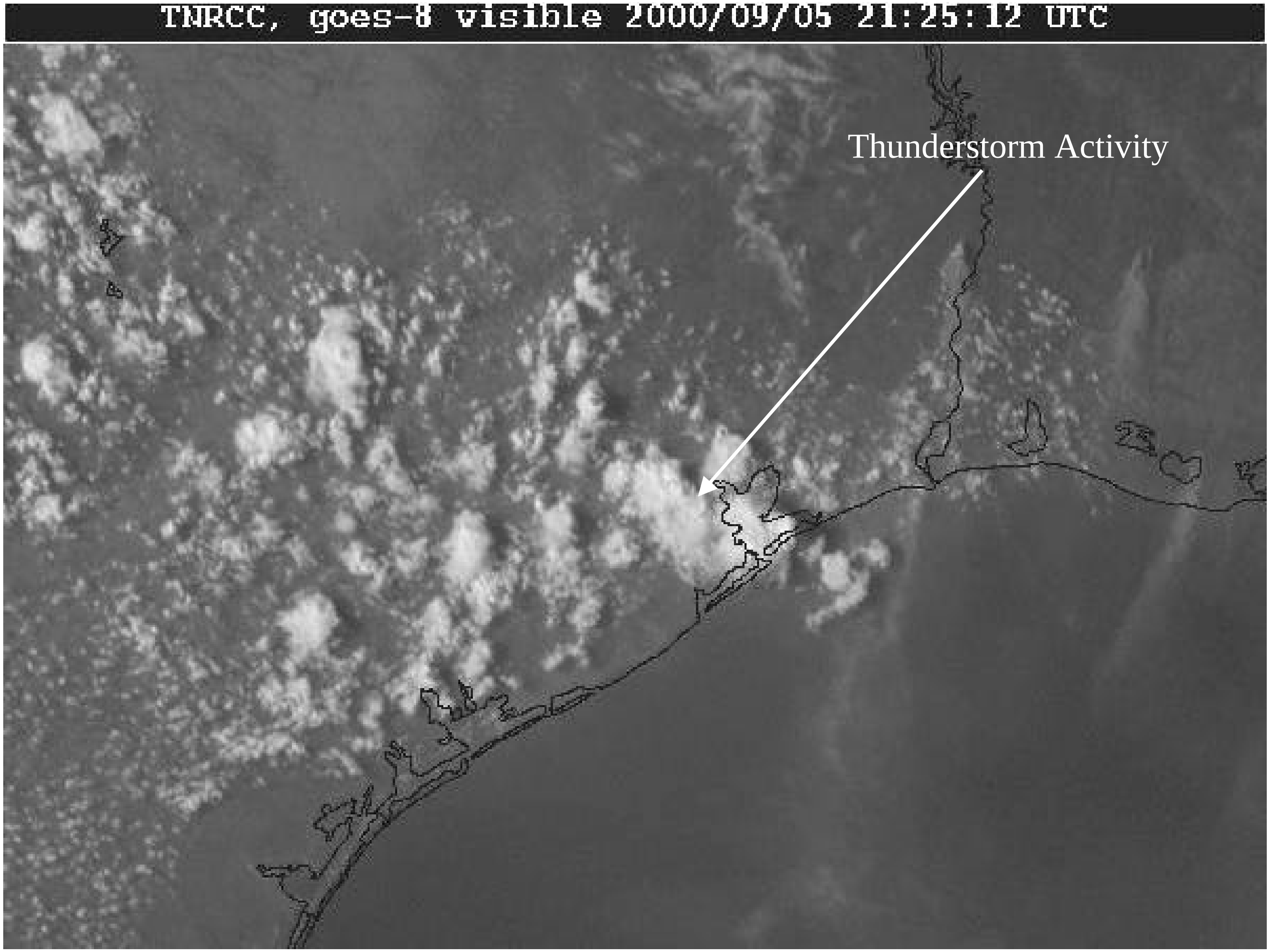


Figure 5-97. Visible satellite imagery at 1525 CST (2125 UTC) on September 5, 2000.

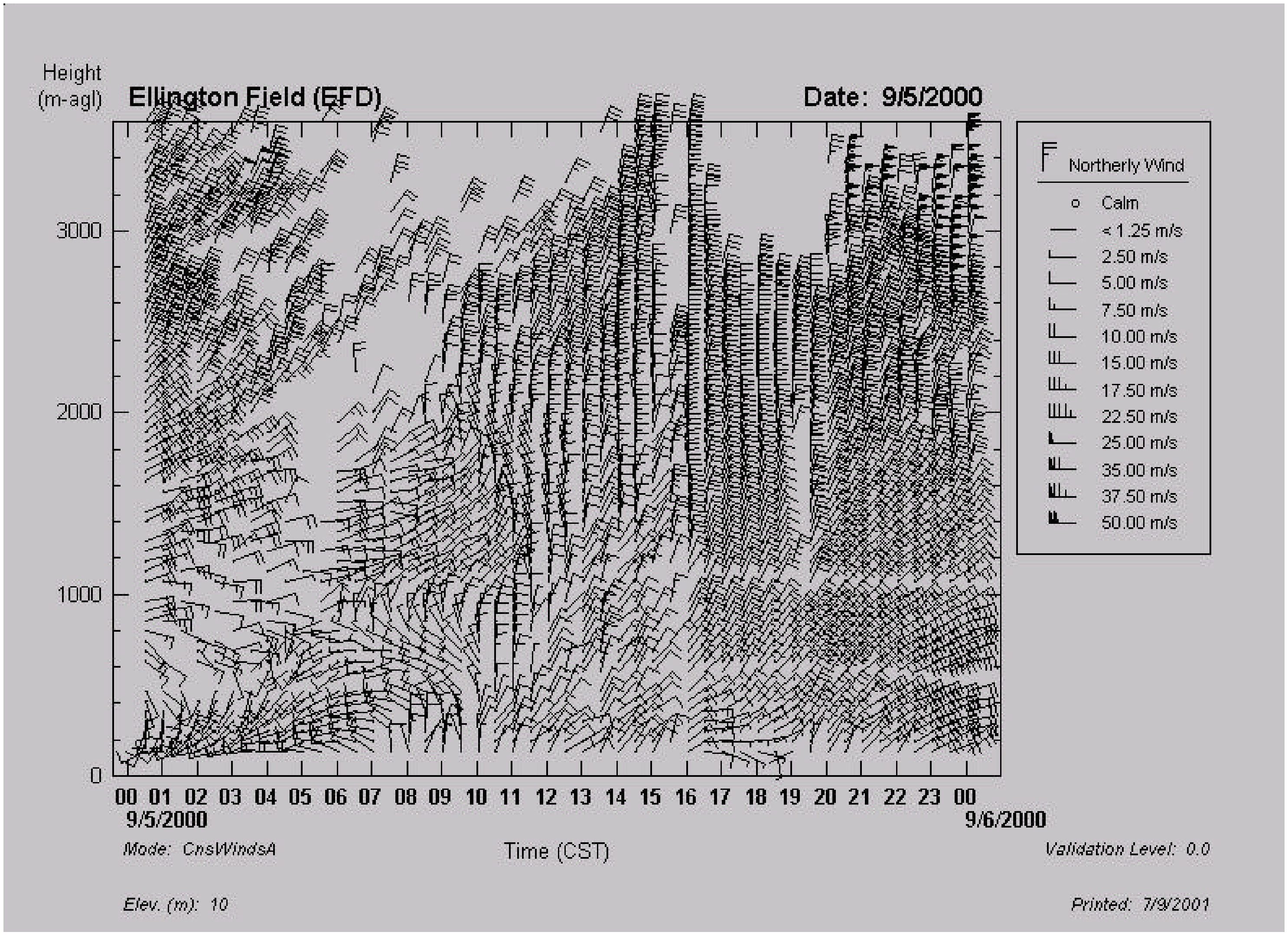


Figure 5-98. Radar wind profiler data for September 5, 2000 at Ellington Field, Houston. The profiler is 10 m above msl.

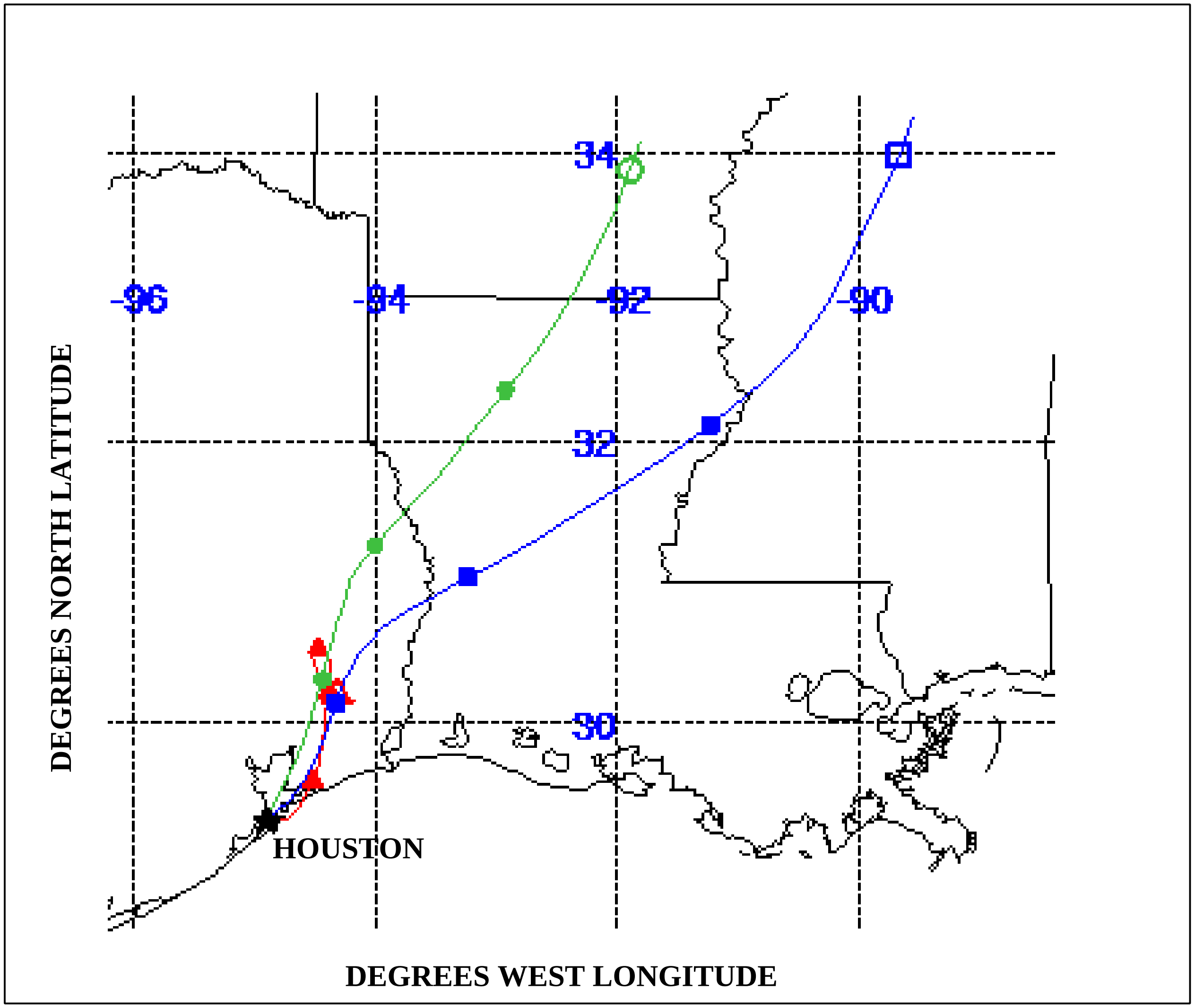


Figure 5-99. Twenty-four-hour back-trajectories for 140 m agl (red line), 700 m agl (blue line), and 1500 m agl (green line) from the general flight area in Houston on September 5, 2000, at 1600 CST.

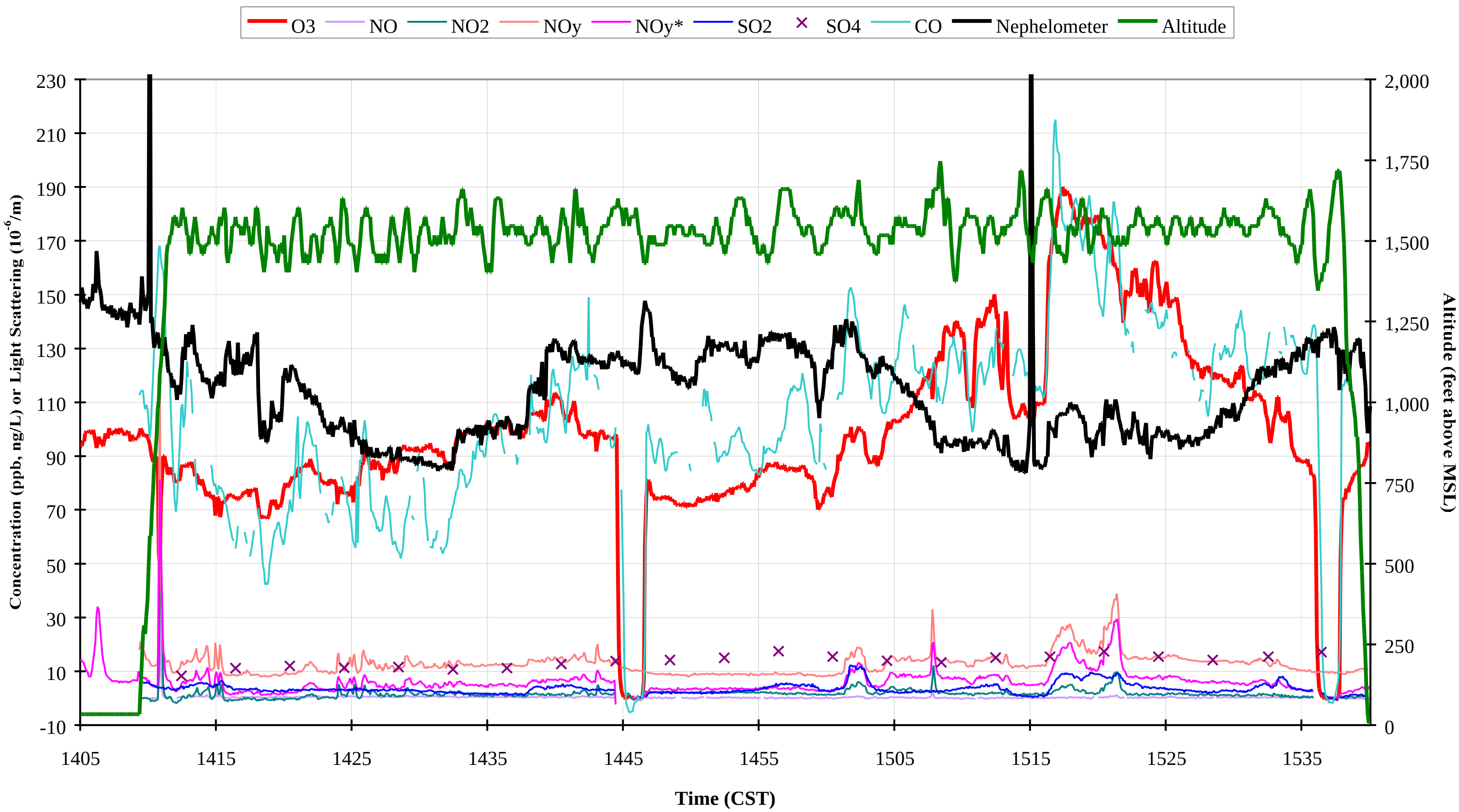


Figure 5-100. Time-series plot of air quality data collected from 1405 CST to 1545 CST on September 5, 2000.

5.12 FLIGHT 150A AND 150B, SEPTEMBER 12, 2000

On September 12, 2000, both a morning and an afternoon flight were performed. The morning flight consisted of a series of box climbs up to about 2000 ft msl (610 m msl), along with one box climb to 10,000 ft msl (3050 m msl) east of Texas City (**Figure 5-101**). When box climbs were not being flown, the flight altitude was maintained at about 1000 ft msl (305 m msl). The afternoon flight included traverses at about 1070 ft msl (305 m msl) west and east of central Houston plus over Galveston Bay and south of Houston. Unlike other afternoon flights, there was no box climb over Galveston Bay (**Figure 5-102**).

5.12.1 Overview of Meteorology and Air Quality

There was a trough of low pressure at 500 mb over the eastern United States and a ridge of high pressure to the west with no strong upper level feature over Texas (**Figure 5-103a**). A surface trough extended from Midland, Texas, due south into Mexico (**Figure 5-103b**). Visible satellite imagery revealed thunderstorms moving from the northeast to the southwest, with scattered activity reaching Houston at about 1200 CST (1800 UTC) (**Figure 5-104**). While thunderstorm activity ceased after a few hours, more thunderstorm activity moving in from the northeast could be seen in the visible satellite imagery.

Figure 5-105 shows the mixing height, as estimated by profiler reflectivity data (C_n^2), at Ellington Field at 1312 ft msl (400 m msl) during the early morning. Beginning around 0900 CST, the mixing height increased to 3280 ft msl (1000 m msl). The mixing heights then increased rapidly, reaching 9184 ft msl (2800 m msl) by 1130 CST (1730 UTC). This increase was related to thunderstorms. Mixing heights were observed to have decreased rapidly to 3280 ft msl (1000 m msl) one-half hour later, followed by a decrease to 984 ft msl (300 m msl) at 1400 CST (2000 UTC).

The 140-m agl, 700-m agl, and 1500-m agl radar profiler back-trajectories indicate that air arriving in central Houston originated that morning about 50 km to the east. The 150-m msl and 700-m msl back-trajectories passed over the Shipping Channel before arriving in central Houston at 1400 CST, where the highest ozone concentrations occurred. Afternoon thunderstorms (due to the surface trough previously mentioned) cleaned out the region during the late afternoon hours.

5.12.2 Spatial Observations of Ozone and NO_x

Morning Horizontal and Vertical

- During the early morning hours, surface ozone concentrations were titrated at all sites, with concentrations ranging from near 0 ppb to 20 ppb. Morning NO_x concentrations range from 100 ppb at CAMS 08 (near central Houston) to around 5 ppb at outlying sites such as CAMS 34 (near Galveston).
- As shown in **Figure 5-106**, carryover ozone concentrations, as observed during a morning box climb east of Texas City, were about 30 to 40 ppb from 1000 ft msl (305 m msl) up to 7500 ft msl (2287 m msl). Other box climbs show similar ozone

concentrations. The profiler wind data indicates that the air at these levels originated from the southeast (**Figure 5-107**).

- Although the exact structure of the pollutants varied among morning box climbs, several morning box climbs showed several different pollutant layers and inversions. The 1000-to-2000 ft msl La Porte box climb (**Figure 5-108**) exemplifies such box climbs. Figure 5-108 shows that there was a temperature inversion at around 1800 ft msl (550 m msl). Beneath the inversion to about 1100 ft msl (335 m msl), ozone concentrations ranged from 0 to 10 ppb, NO_y concentrations were as high as 170 ppb, and NO concentrations as high as 130 ppb. Collocated SO_2 concentrations were about 3 to 15 ppb. The very low ozone concentrations and high NO concentrations indicate that this layer was fresh. Profiler winds were from the south by southeast in this layer at the time of this box climb. Above the inversion, NO_y, NO, and SO_2 concentrations decreased to 0 ppb, and ozone concentrations increased to about 30 ppb, which concentrations were similar to those observed during the Texas City box climb.

Afternoon Horizontal

- The highest surface ozone concentration was 100 ppb at CAMS 08 at 1200 CST north of central Houston. Only three CAMS sites reported ozone concentrations in excess of 90 ppb, all located in central Houston. The highest ozone concentrations were observed at 1200 CST at almost all the sites, with drops in concentration after that probably due to the onset of thunderstorms.
- The highest ozone concentration observed by the aircraft was around 110 ppb at 1100 ft msl (335 m msl) at 1340 CST over central Houston. This peak coincided with local NO_y and SO_2 concentration peaks of 25 and 10 ppb, respectively (**Figure 5-109**). Other ozone peaks in central Houston were also associated with SO_2 (Figure 5-109).
- There were no box climbs during the afternoon flight. The ascending and descending profiles on takeoff and landing showed ozone concentrations of 30 to 40 ppb, NO_y concentrations of 3 to 10 ppb, and NO concentrations of 0 to 2 ppb, indicating that the ozone layer was confined to central and north Houston.

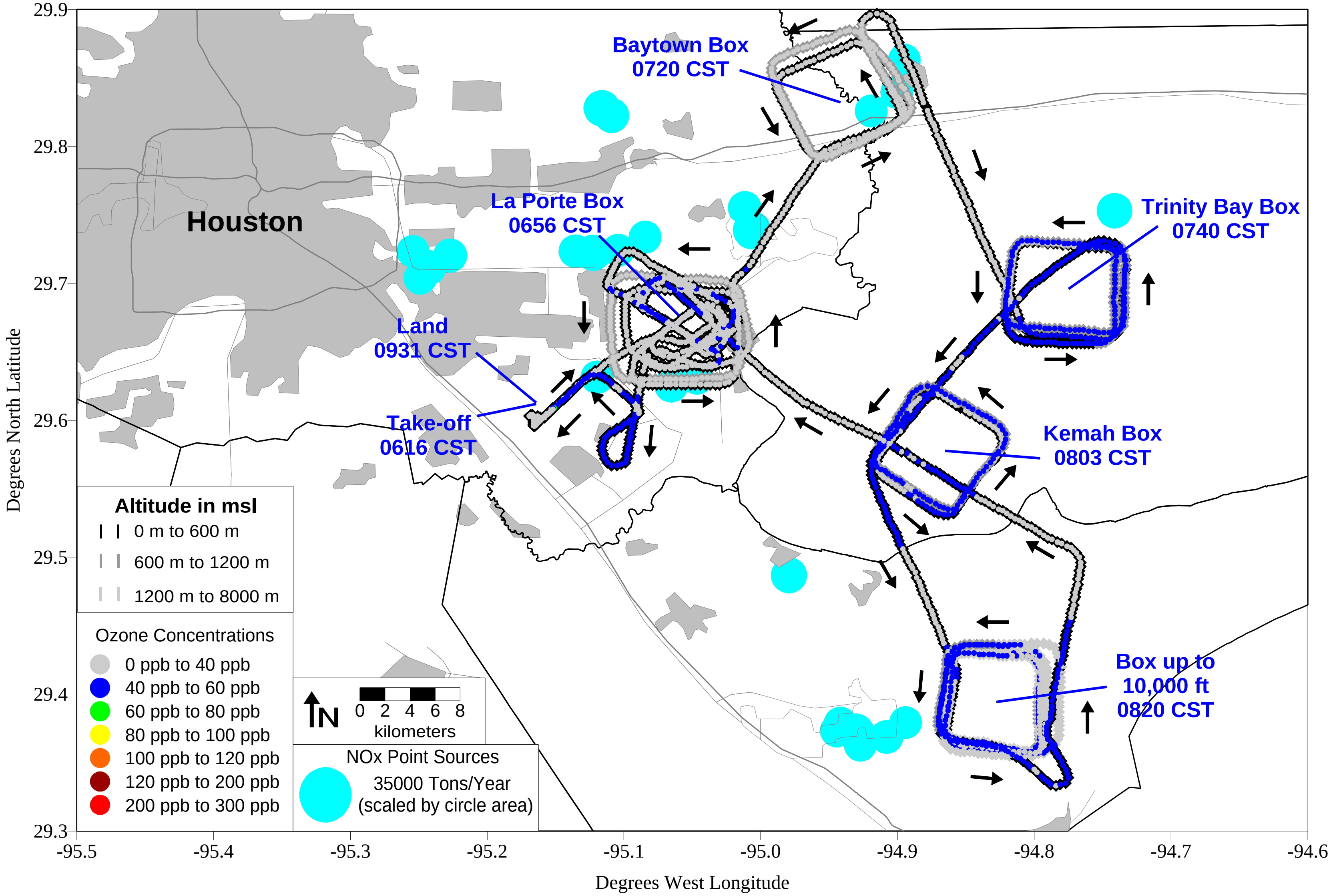


Figure 5-101. Flight 150 flight position, altitude, and aloft ozone concentrations on the morning of September 12, 2000.

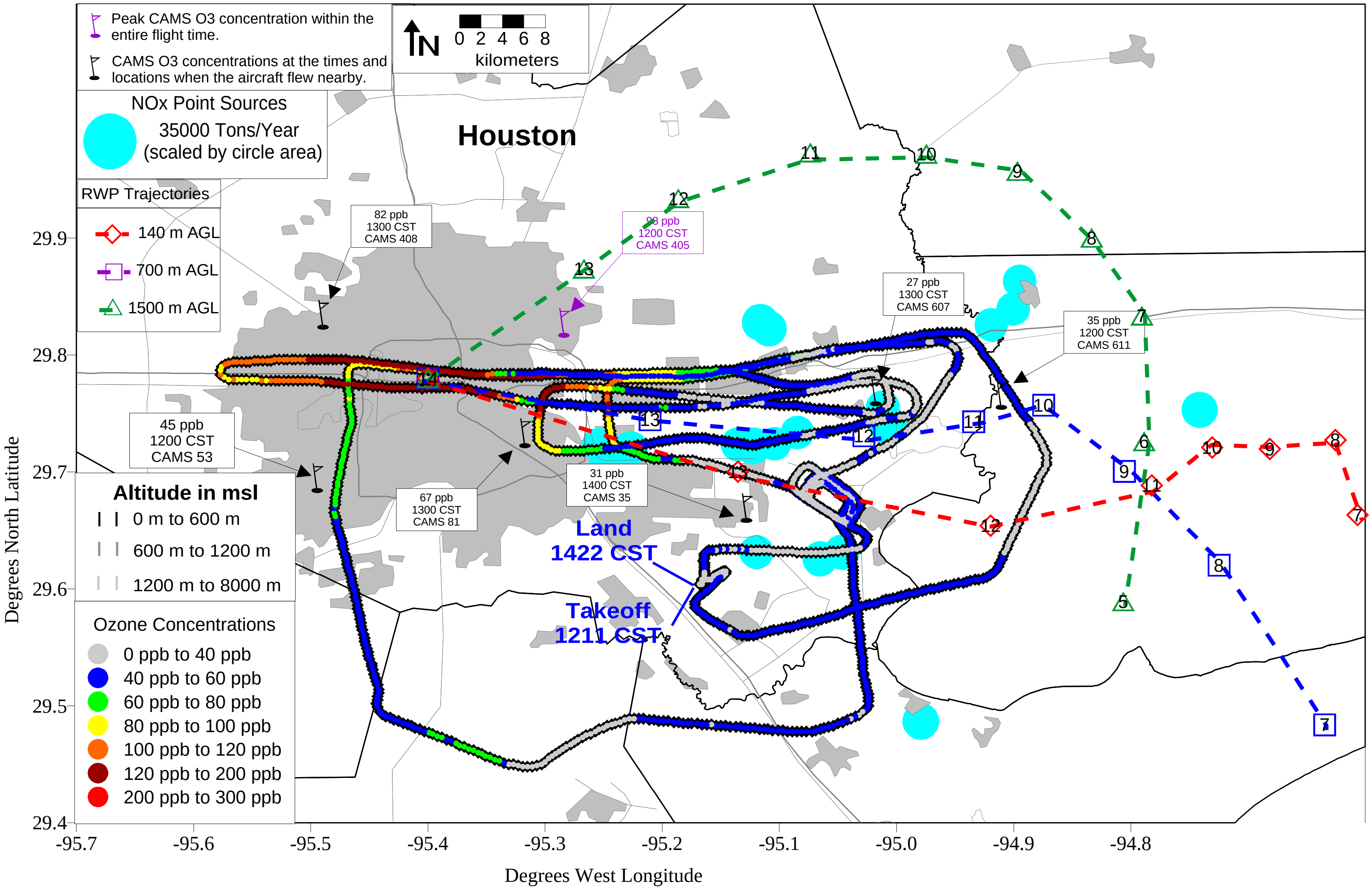


Figure 5-102. Flight 150 flight position, altitude, aloft ozone concentrations, and CAMS surface ozone concentrations on the afternoon of September 12, 2000.

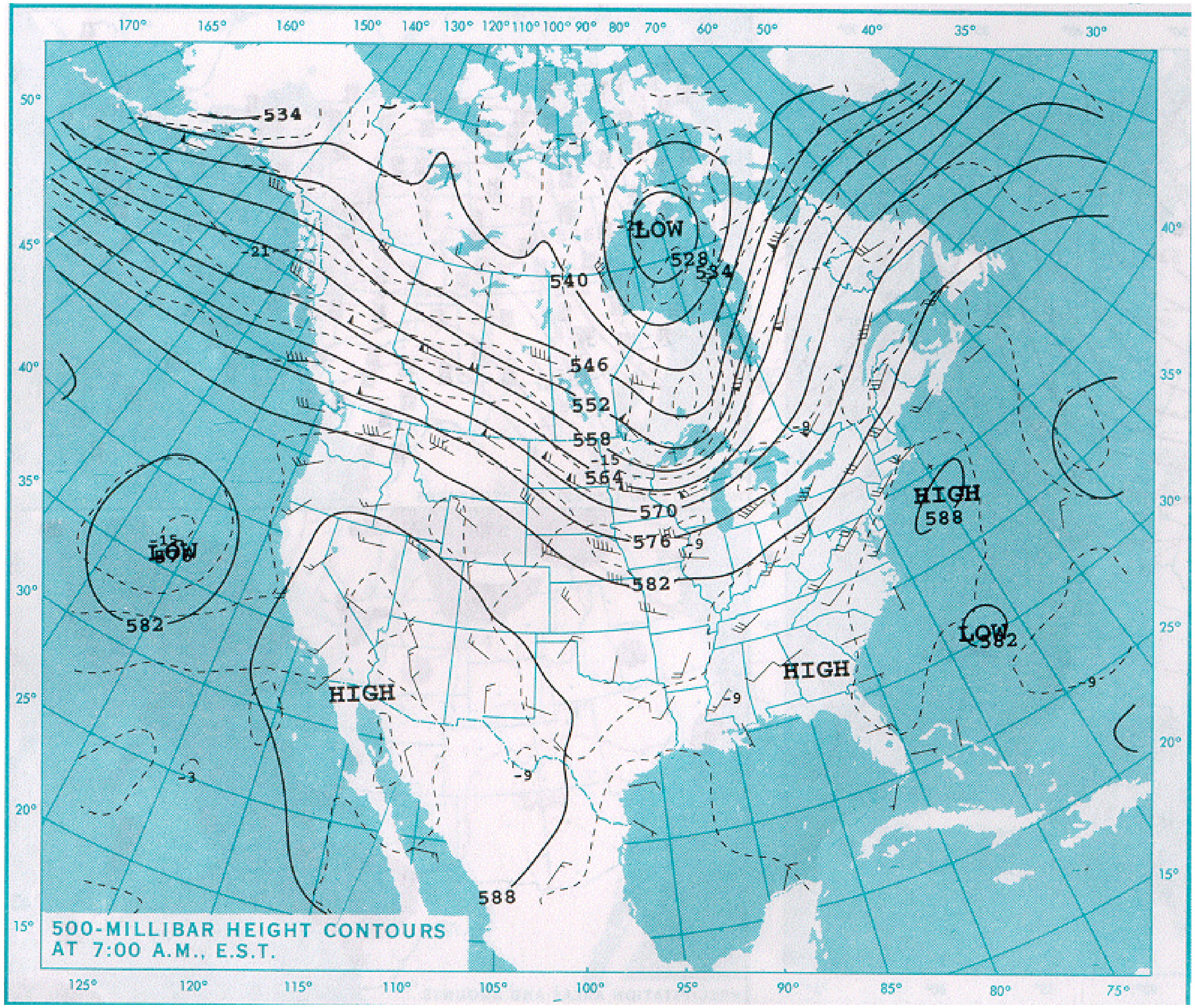


Figure 5-103a. Height contours of the 500-mb pressure surface at 0600 CST on September 12, 2000.

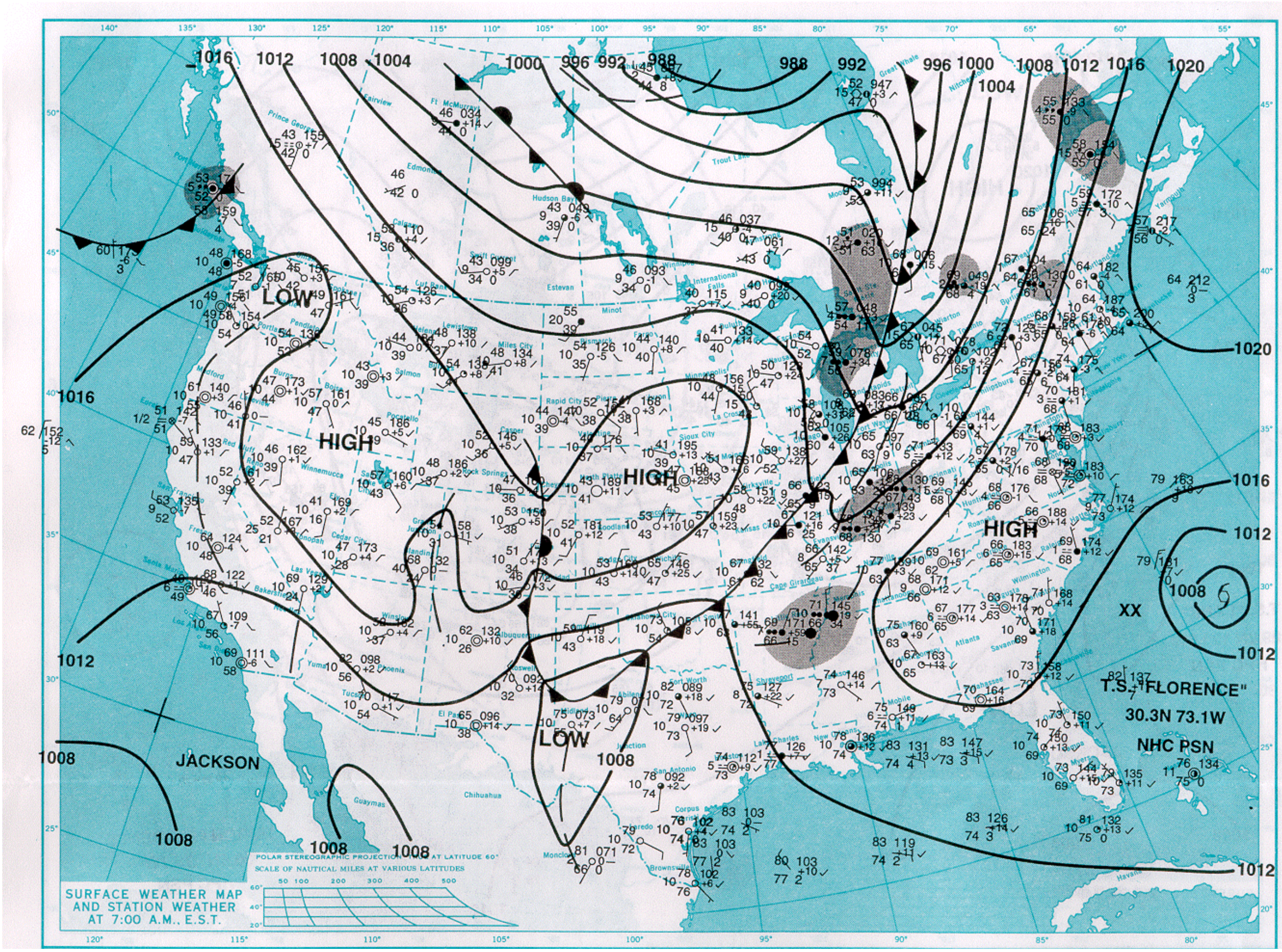


Figure 5-103b. Surface analysis at 0600 CST on September 12, 2000.

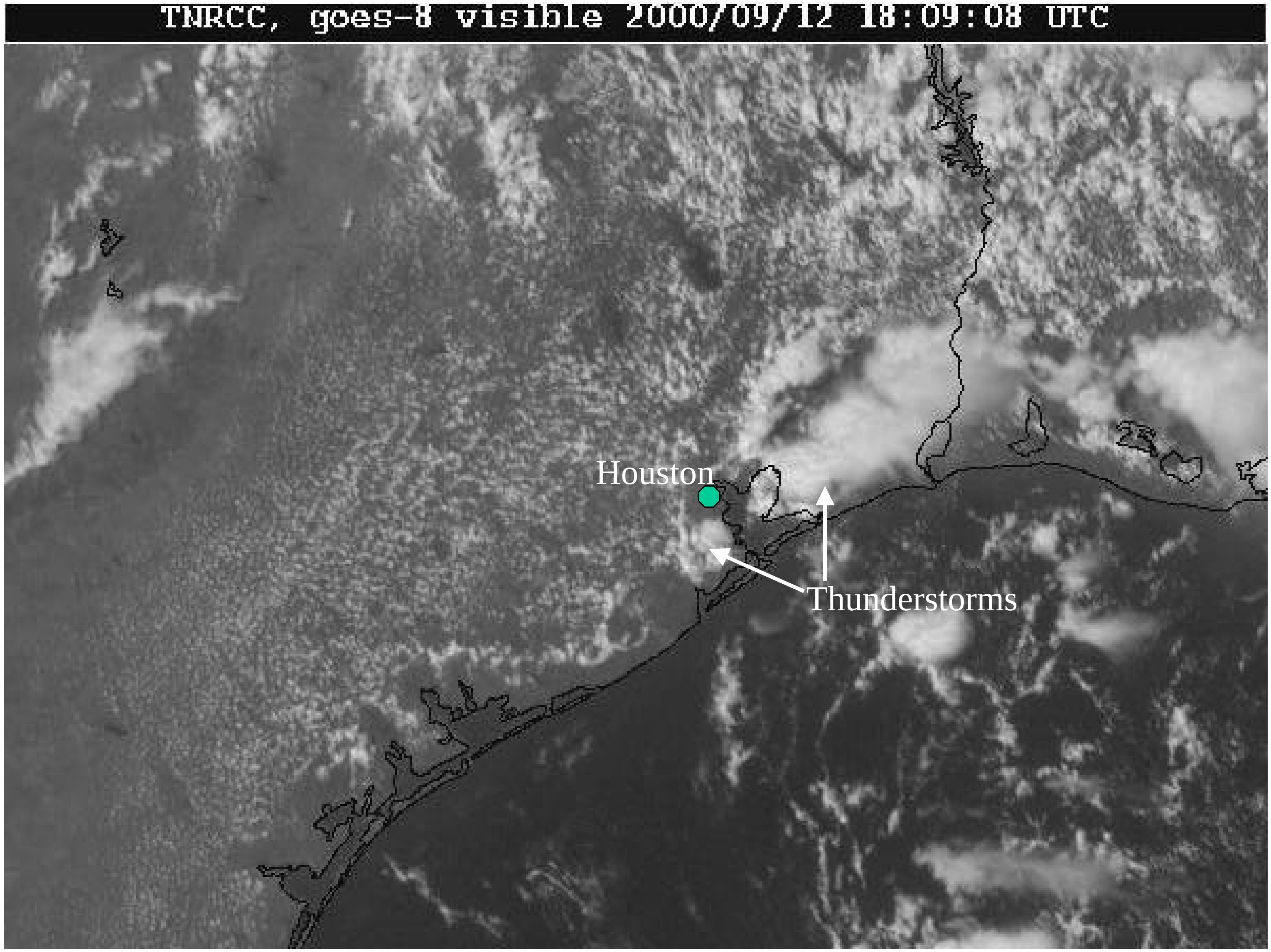


Figure 5-104. Visible satellite imagery at 1209 CST (1809 UTC) on September 12, 2000.

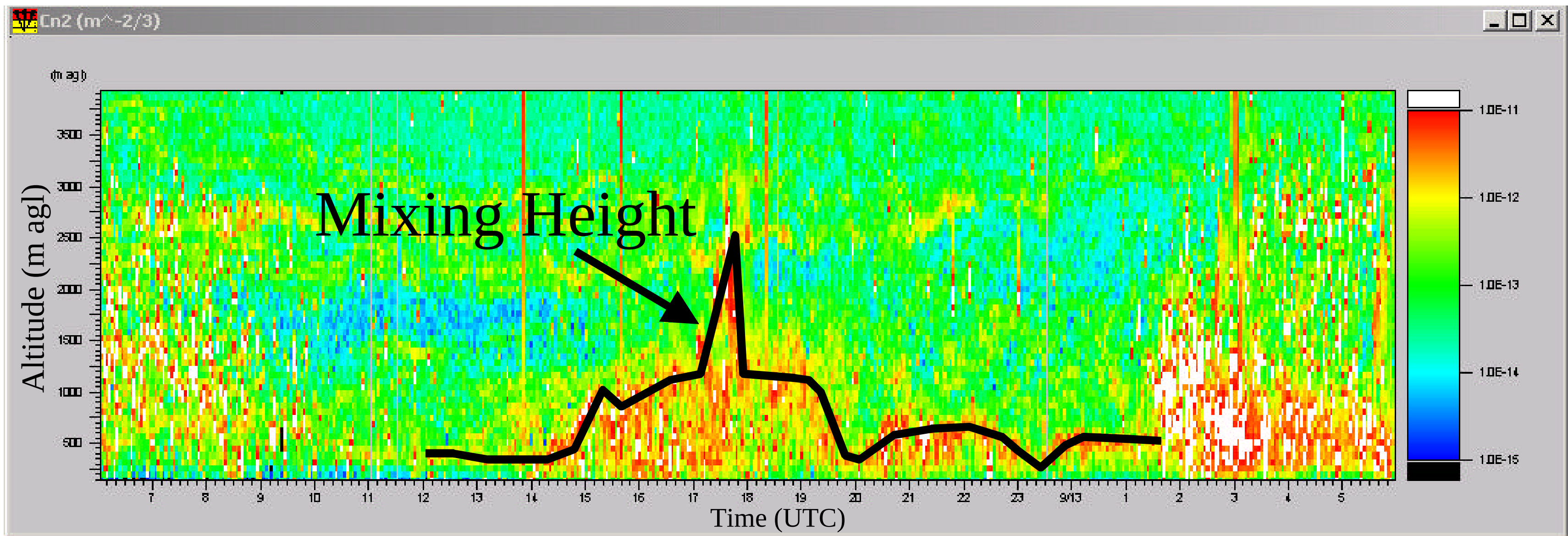


Figure 5-105. Radar wind profiler reflectivity data (C_n^2) and estimated mixing height for September 12, 2000 at Ellington Field, Houston. The profiler is 10 m above msl.

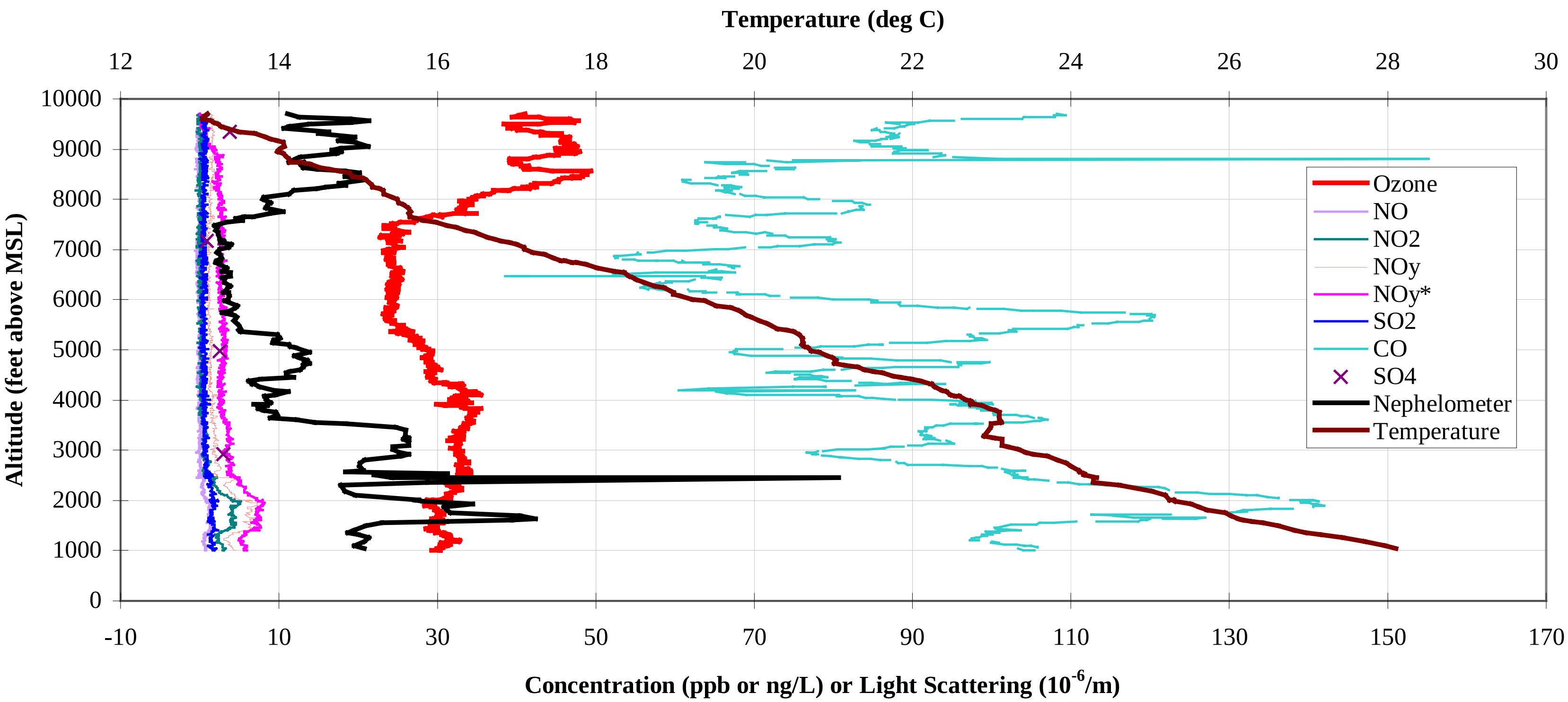


Figure 5-106. Vertical profile of air quality and temperature data collected over Galveston Bay (east of Texas City) from 0820 to 0836 CST on September 12, 2000.

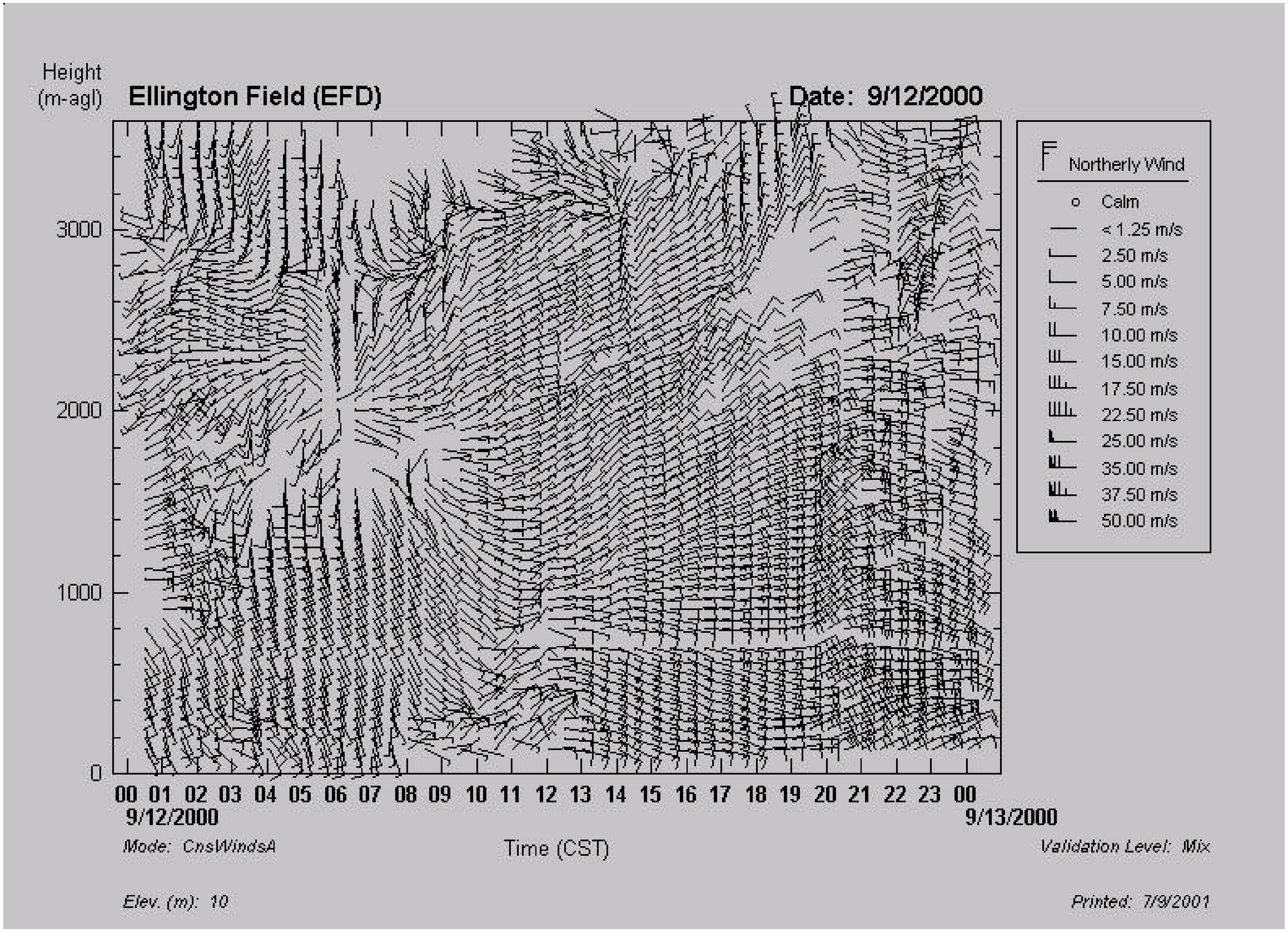


Figure 5-107. Radar wind profiler data for September 12, 2000, at Ellington Field, Houston. Note that the profiler is 10 m above msl.

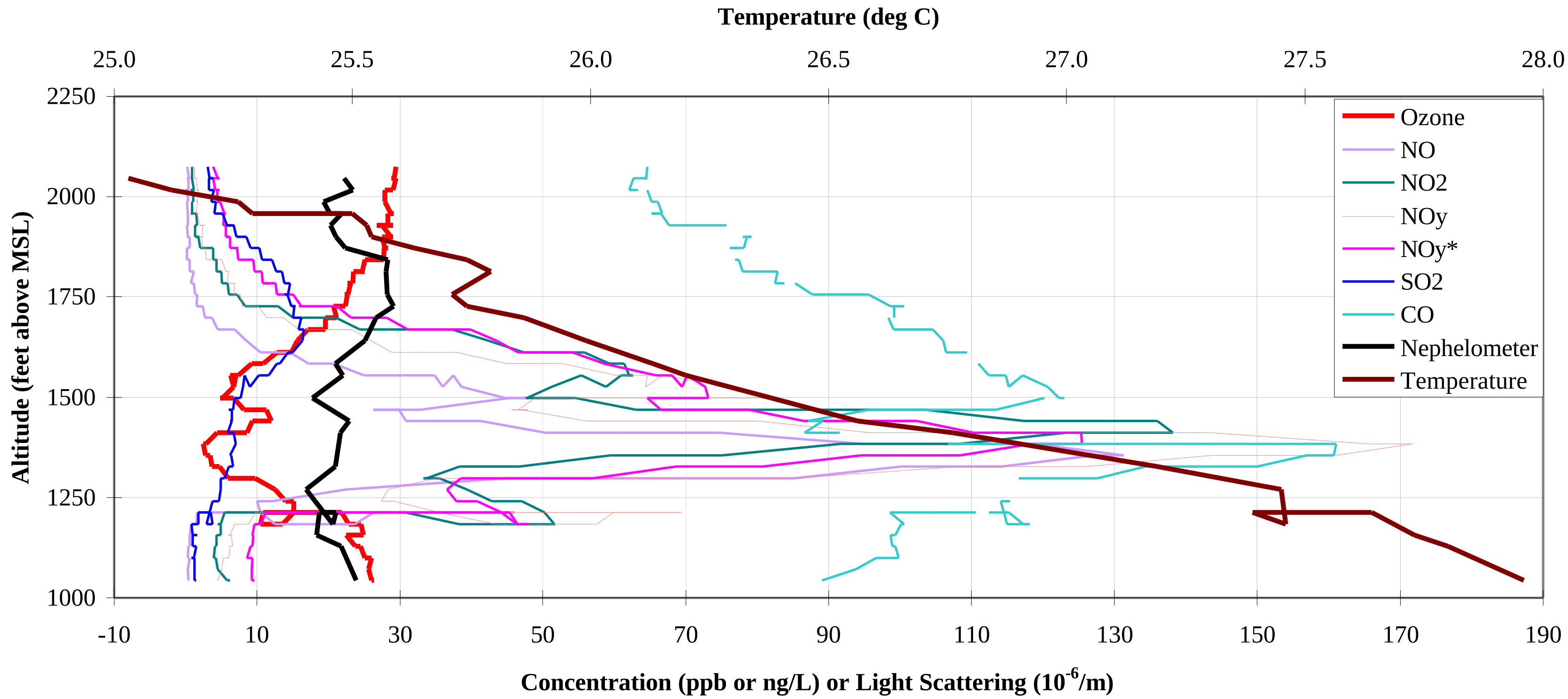


Figure 5-108. Vertical profile of air quality and temperature data collected over La Porte, Texas, from 0703 to 0706 CST on September 12, 2000.

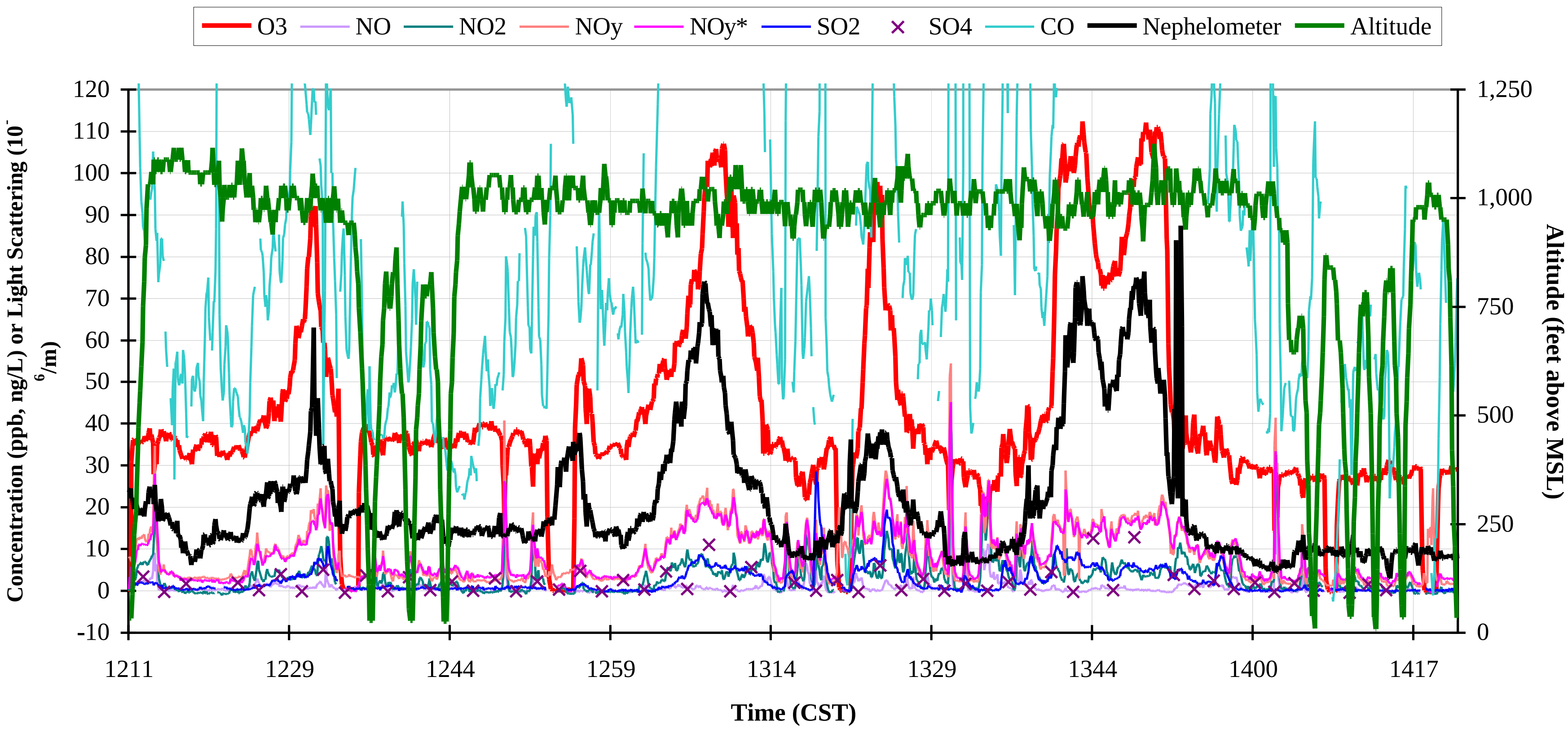


Figure 5-109. Time-series plot of air quality and temperature data collected from 1211 to 1422 CST on September 12, 2000.

6. POLLUTION ROSE PLOTS AND COMPARISON OF RADAR PROFILER AND AIRCRAFT WIND DATA

6.1 PURPOSE

Pollution rose plots using aloft ozone data collected by the Baylor aircraft and Ellington Field profiler wind data were created to view the relationship between aloft ozone concentrations and wind direction. Although the aircraft measured winds, analysis of the data showed a high bias and uncertainty; thus, the aircraft wind data were not used to create the pollution rose plots. The wind data were deemed suspect based on a comparison between the radar profiler winds and the aircraft winds, which is discussed in Section 6.2. Section 6.3 presents the pollution rose plots.

6.2 COMPARISON BETWEEN AIRCRAFT AND RADAR PROFILER WIND DATA

Validated radar profiler wind data collected at Ellington Field were compared to wind data collected by the Baylor aircraft to check the quality of the aircraft wind data. The aircraft wind data used in the comparison were collected during the 2000-ft msl La Porte box climb and the 10,000-ft Galveston Bay box climb. These box climbs were selected for comparison because of their close proximity to Ellington Field and because these box climbs were flown on several days.

6.2.1 Method

Aircraft measurements of wind speed and wind direction were reported in 5-second intervals. Typically, there were 5 to 10 data points of valid data with blocks of invalid data in between the valid blocks. In each valid block of data, a relatively constant wind direction with one or two outlying values (typically not varying more than +/-20°) was often observed. The wind direction that occurred most frequently was used as the observed value for that block. The altitudes and times of data from both the aircraft and radar profiler were matched to ensure a consistent comparison.

To understand how the wind instrument performs under varying aircraft movement, the aircraft ascent/descent rate and the variability in the aircraft heading were also noted. If the aircraft heading varied between a few consecutive data points by 0–1º, the aircraft movement was considered constant. If the aircraft heading varied by 2–2.9º, the aircraft movement was considered variable. If the aircraft heading varied by 3+º, the aircraft movement was considered highly variable. In many of the highly variable cases, the aircraft was taking wind measurements during a turn.

For 42 selected points, the difference between wind directions for each altitude was calculated as aircraft wind direction minus profiler wind direction. The difference between wind speeds for each altitude was calculated as aircraft wind speed minus profiler wind speed. The data used in these calculations and the differences are shown in **Table 6-1**. The average differences for both wind direction and wind speed were calculated to examine the bias of the data. However, because a zero bias does not necessarily imply a zero uncertainty in the data points, the root mean-square difference was also calculated.

6.2.2 Results and Conclusion

The difference between the aircraft wind direction and the profiler wind direction varied from +97º to –153º. The difference between the aircraft wind speed and the profiler wind speed varied from –10 to +10 knots. The calculations show that the wind directions observed by the aircraft contain a bias of –17.9º, and a root mean square difference (uncertainty) of 49.1º when compared to the radar profiler wind direction data. The calculations also show that the wind speeds had a bias of –0.6 knots and a rather high uncertainty of 4.2 knots. In some cases, the aircraft wind data compares well with the radar profiler wind data, such as the Galveston Bay spiral on August 19, 2000. However, the aircraft wind data more often compares poorly with the radar profiler wind data. For the data in Table 6-1, the difference in winds is independent of the variability in the aircraft's movement.

In conclusion, the wind data as measured by the aircraft showed a high level of uncertainty; therefore, the data can not be used confidently without further detailed validation.

6.3 POLLUTION ROSE PLOTS

Pollution rose plots were created using radar profiler and aircraft data. Radar profiler winds at Ellington Field were vector-averaged using two hours of wind data surrounding the time of the aircraft measurements. Ozone was measured during six box climbs: the 1000- to 2000-ft morning box climbs over La Porte, Baytown, Trinity, and Kemah; the 10,000-ft box climb just east of Texas City; and the afternoon 5000-ft box climb over Galveston Bay. For each morning box climb, the ozone data and wind data collected from 1000 to 2000 ft were averaged and pollution rose plots were produced. An additional pollution rose plot was produced using the morning data from 2000 to 5000 ft over Galveston Bay. For afternoon box climbs over Galveston Bay, the ozone data and wind data collected from 1000 to 5000 ft were averaged and pollution rose plots were produced. The 5000-ft top was chosen because it was approximately the peak altitude of the daytime boundary layer for flight days. Only four to six box climbs at each location contained sufficient data to create the pollution rose plots.

Figures 6-1 through 6-5 show the pollution rose plots for the 1000- to 2000-ft msl morning box climbs. **Figure 6-6** shows the pollution rose plot for the 2000- to 5000-ft msl morning box climb east of Texas City. **Figure 6-7** shows the pollution rose plot for the 1000- to 5000-ft msl afternoon box climb over Galveston Bay. The sector colors indicate the average ozone concentrations in the box climb. Each sector indicates the direction from which the wind blew, and is binned in 10° increments. The frequency of occurrence (percent) is also shown. Since so few days are represented, most sectors represent individual days.

Table 6-1. Comparisons between selected radar profiler winds and aircraft winds.

Date	Time (CST) hhmmss	Elevation(m msl)	Ascending or Descending	Aircraft Wind Direction (degrees)	Aircraft Wind Speed (knots)	Radar Profiler Elevation (m msl)	Radar Profiler Wind Direction	Radar Profiler Wind Speed (knots)	Heading Comments	Difference Between the Aircraft WD and Profiler WD	Difference Between the Aircraft WS and Profiler WS
8/19/00	083025	329	Ascending	230	5	302	227	4	Constant Heading	3	1
8/19/00	083040	363	Ascending	250	5	357	236	5	Constant Heading	14	0
8/19/00	083225	598	Ascending	170	5	577	216	5	Constant Heading	-46	0
8/19/00	083605	1175	Ascending	150	5	1182	213	8	Highly Variable	-63	-3
8/19/00	083625	1230	Ascending	130	10	1237	215	8	Highly Variable	-85	2
8/19/00	084055	1916	Ascending	130	20	1896	126	18	Constant Heading	4	2
8/19/00	084400	2418	Ascending	110	20	2391	110	24	Highly Variable	0	-4
8/19/00	085930	3070	Descending	120	35	3051	119	34	Variable	1	1
8/19/00	090655	1460	Descending	120	15	1456	208	5	Constant Heading	-88	10
8/19/00	090900	858	Descending	330	5	852	233	5	Highly Variable	97	0
8/21/00	081010	712	Ascending	220	5	687	242	10	Constant Heading	-22	-5
8/21/00	081405	1260	Ascending	130	10	1292	138	10	Highly Variable	-8	0
8/21/00	081600	1545	Ascending	90	5	1566	139	12	Constant Heading	-49	-7
8/21/00	081900	1968	Ascending	110	10	1896	121	13	Variable	-11	-3
8/21/00	082040	2202	Ascending	120	15	2226	114	8	Constant Heading	6	7
8/21/00	082545	2874	Ascending	80	15	2886	113	18	Highly Variable	-33	-3
8/21/00	082710	3029	Ascending	110	20	2996	108	19	Constant Heading	2	1
8/22/00	073615	343	Ascending	60	10	357	33	13	Constant Heading	27	-3
8/22/00	074310	1435	Ascending	110	15	1456	117	12	Highly Variable	-7	3
8/22/00	074755	2105	Ascending	120	20	2116	121	23	Constant Heading	-1	-3
8/22/00	080445	1409	Descending	110	15	1401	130	12	Variable	-20	3
8/22/00	080925	287	Descending	70	5	302	49	15	Constant Heading	21	-10
8/29/00	083345	2088	Descending	170	15	2116	143	11	Variable	27	4
8/29/00	083505	1807	Descending	130	10	1786	156	10	Constant Heading	-26	0
8/29/00	083755	1100	Descending	50	5	1127	221	9	Constant Heading	-171	-4
8/29/00	083810	1044	Descending	20	5	1072	227	9	Constant Heading	-153	-4
8/30/00	075030	817	Ascending	230	5	797	232	10	Constant Heading	-2	-5
8/30/00	080715	3070	Constant	50	10	2996	123	15	Constant Heading	-73	-5
8/30/00	080835	2887	Descending	140	10	2886	117	15	Variable	23	-5
8/30/00	081210	1850	Descending	90	15	1841	88.4	7	Highly Variable	1.6	8
8/30/00	081800	312	Descending	290	15	283	283	9	Variable	7	6
8/16/00	063815	451	Ascending	210	10	467	228	12	Constant Heading	-18	-2
8/16/00	064345	608	Ascending	240	15	632	226	12	Variable	14	3
8/16/00	074515	608	Descending	210	10	632	230	10	Constant Heading	-20	0
8/19/00	071950	357	Ascending	200	5	357	216	6	Highly variable	-16	-1
8/19/00	072115	591	Ascending	180	10	577	199	8	Highly variable	-19	2
8/19/00	072640	539	Descending	190	10	577	199	8	Constant Heading	-9	2
8/21/00	064110	618	Constant	220	10	632	221	12	Constant Heading	-1	-2
8/21/00	064255	618	Constant	170	5	632	221	12	Variable	-51	-7
8/30/00	063000	333	Ascending	280	10	357	261	16	Variable	19	-6
8/30/00	063140	629	Constant	230	10	632	243	10	Constant Heading	-13	0
8/30/00	063600	612	Constant	230	10	632	243	10	Constant Heading	-13	0

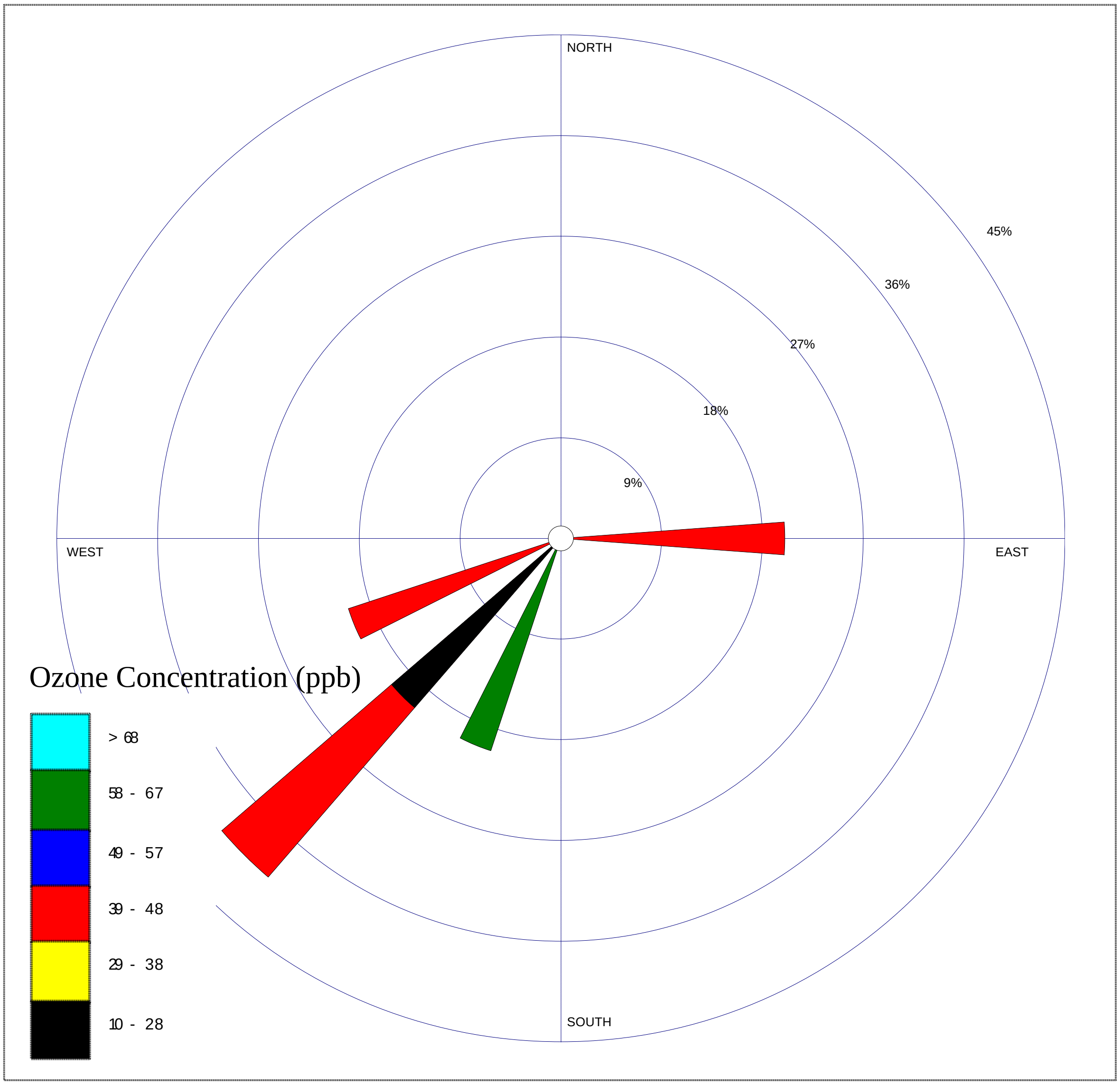


Figure 6-1. Ozone concentration rose plot for the morning 1000- to 2000-ft msl (305- to 610-m msl) box climbs over La Porte.

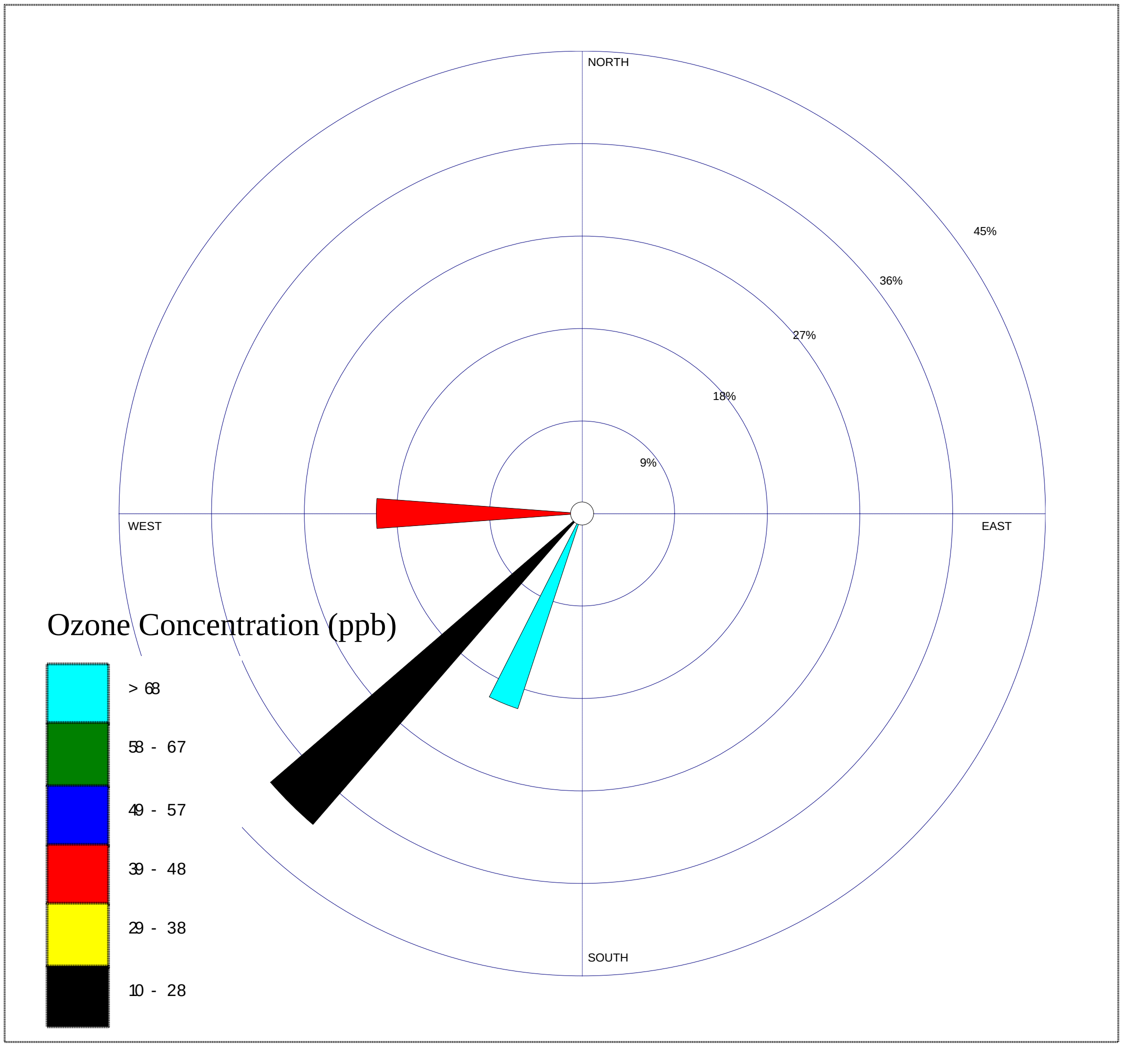


Figure 6-2. Ozone concentration rose plot for the morning 1000- to 2000-ft msl (305- to 610-m msl) box climbs over Baytown.

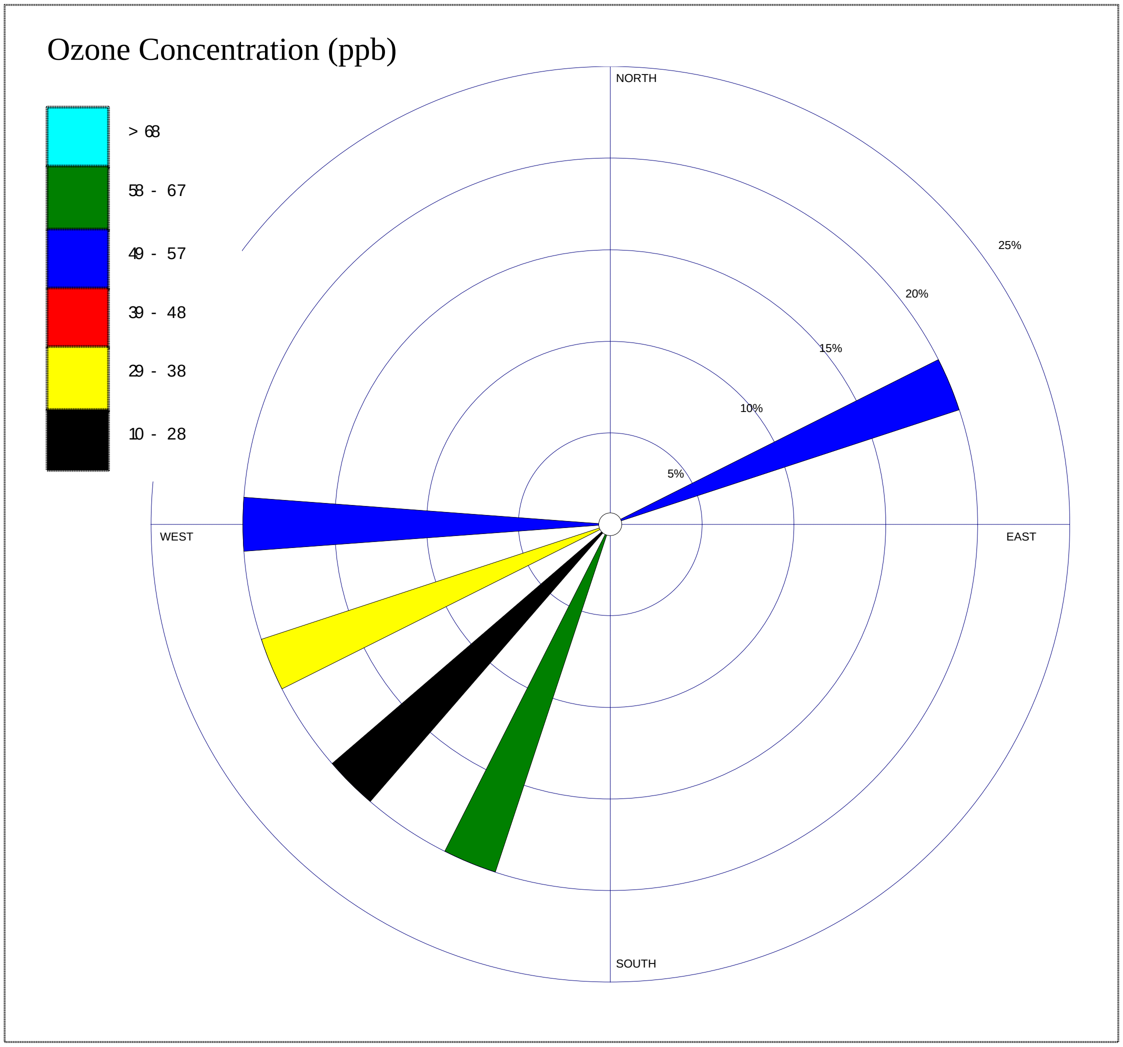


Figure 6-3. Ozone concentration rose plot for the morning 1000- to 2000-ft msl (305- to 610-m msl) box climbs over Trinity Bay.

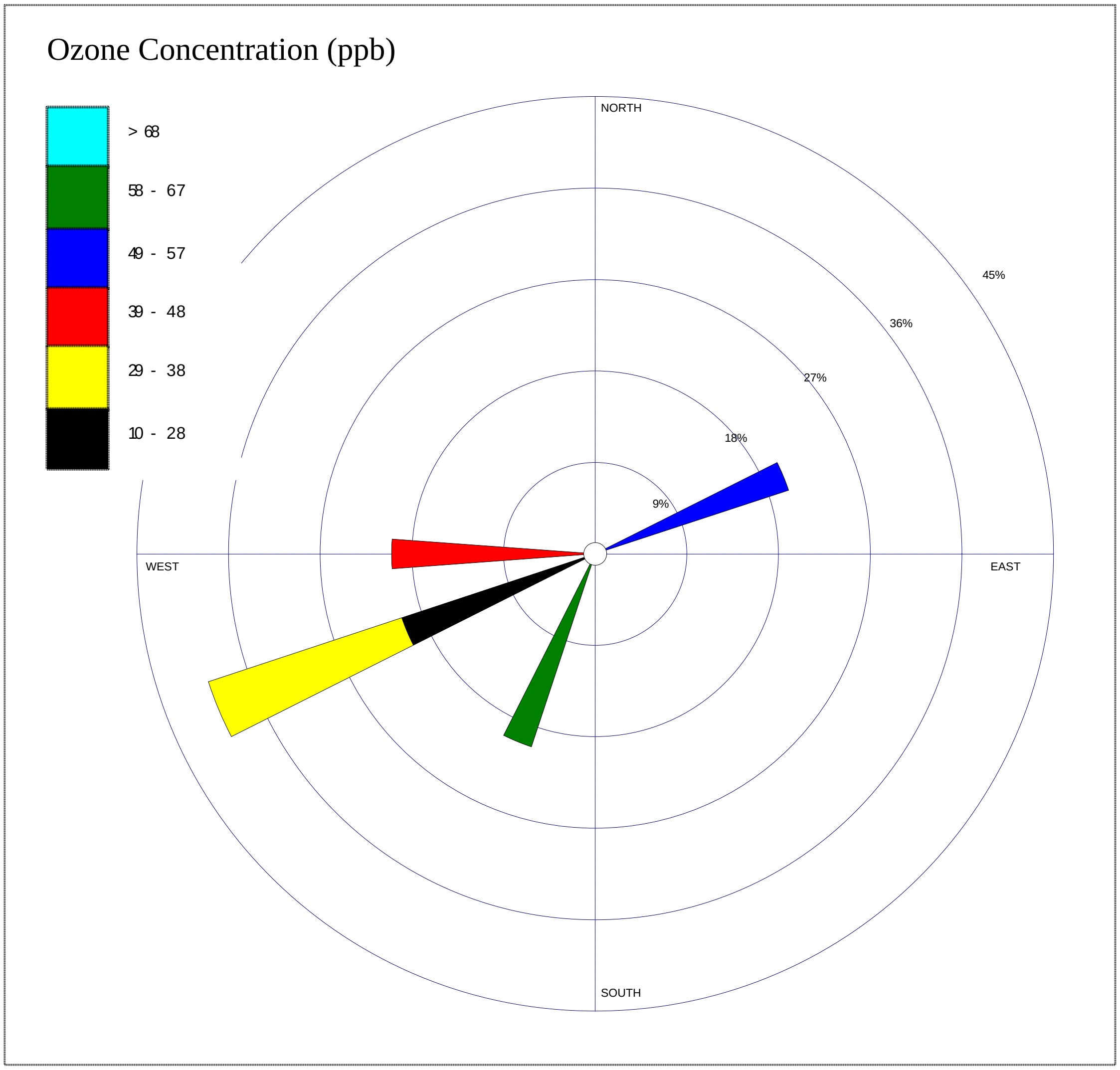


Figure 6-4. Ozone concentration rose plot for the morning 1000- to 2000-ft msl (305- to 610-m msl) box climbs over Kemah.

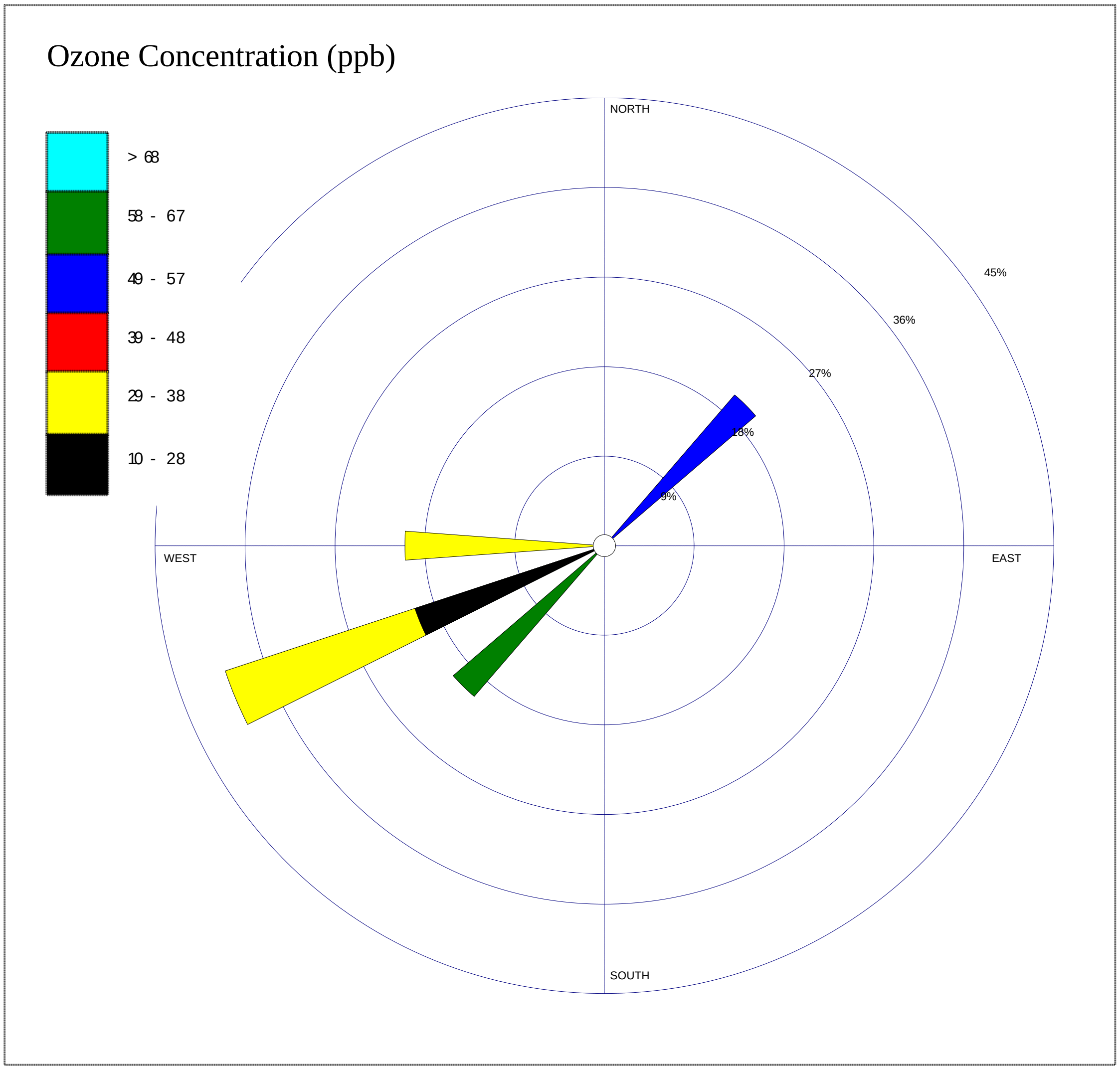


Figure 6-5. Ozone concentration rose plot for the morning 1000- to 2000-ft msl (305- to 610-m msl) box climbs over the coast of Texas City.

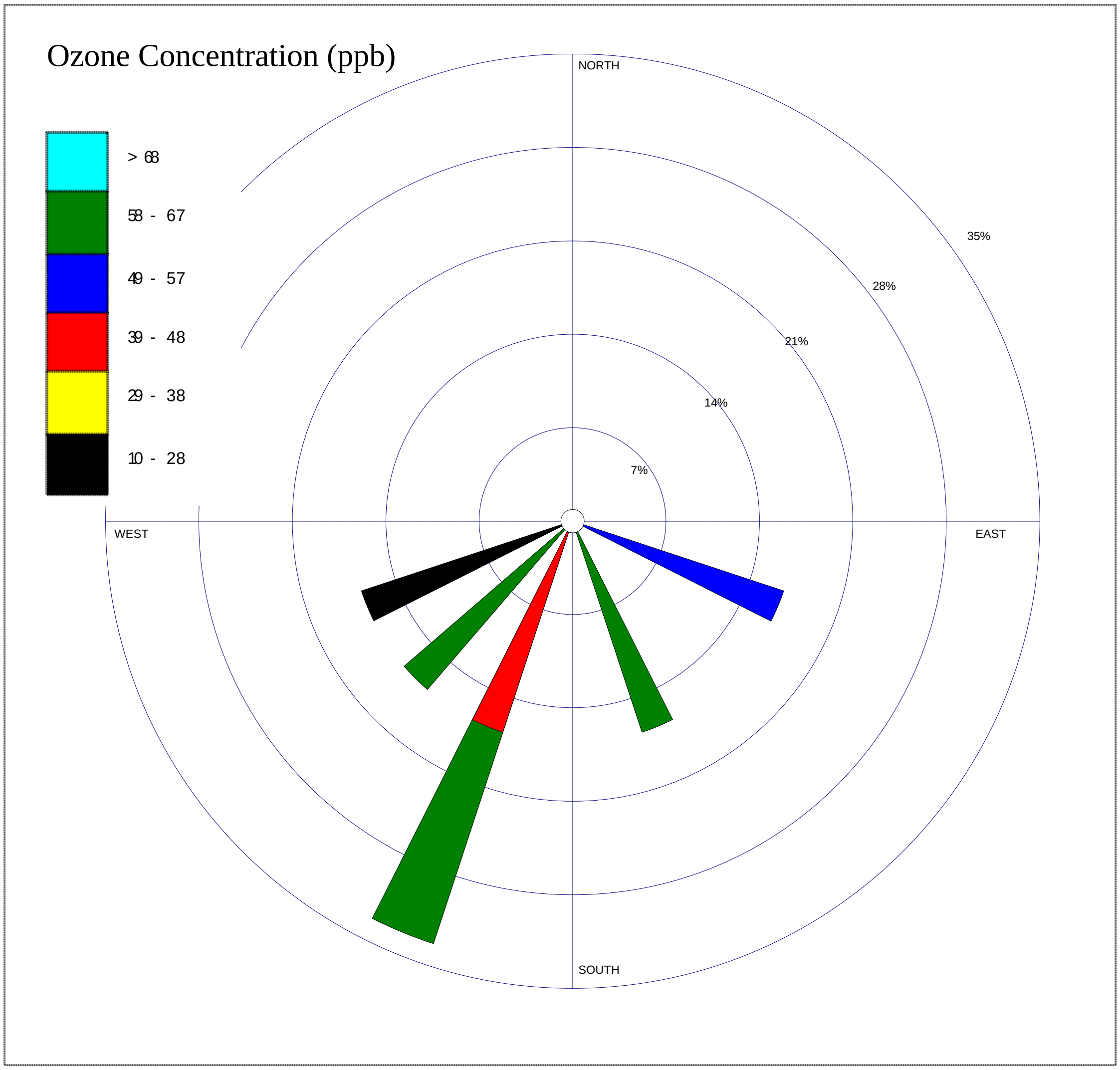


Figure 6-6. Ozone concentration rose plot for the morning 2000- to 5000-ft msl (610- to 1524-m msl) box climbs over the coast of Texas City.

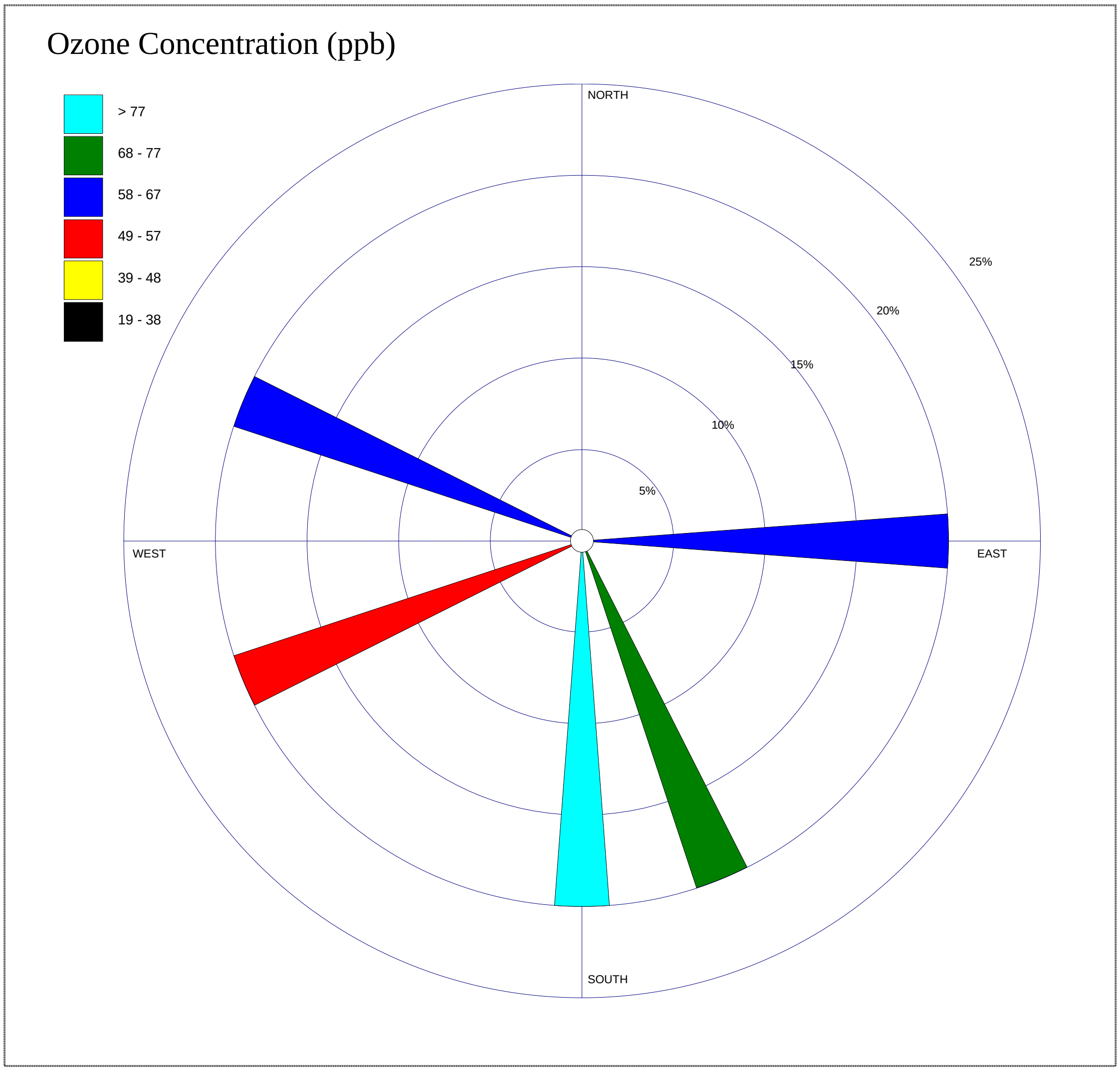


Figure 6-7. Ozone concentration rose plot for the afternoon 1000- to 5000-ft msl (305- to 1524-m msl) box climbs over Galveston Bay.

6.4 RESULTS

A brief review of the wind rose plots reveals the following:

- The pollution rose plot for the morning box climb over La Porte shows wind directions from the southwest for each day except one [August 22, 2000], when an east wind was observed (Figure 6-1). The ozone concentrations varied from 18 to 64 ppb during the southwest flow. Although a different wind direction was observed on August 22, 2000, the average ozone concentration of the layer (44 ppb) was close to midrange of the other days.
- The pollution rose plot for the morning box climb over Baytown shows wind directions that vary from west to south-southwest (Figure 6-2). Like the La Porte pollution rose plot, the ozone concentrations vary from 15 to 69 ppb. Data taken by the aircraft on one day [August 22, 2000] during the Baytown spiral were insufficient to produce a pollution rose plot.
- The pollution rose plot for the morning box climb over Trinity Bay shows wind directions mostly from the west-southwest (Figure 6-3). The ozone concentrations varied from 18 to 66 ppb during the days of the west-to-southwest flow. On one day (August 22, 2000), the winds were from the east-northeast and ozone concentrations (51 ppb) were higher than average for the five days.
- The pollution rose plot for the morning box climb over Kemah shows the west-southwest flow and like other morning spirals, it shows widely variable ozone concentrations (Figure 6-4). On one day [August 22, 2000], the winds were from the east-northeast and ozone concentrations (56 ppb) were higher than the average of other Kemah spirals.
- The pollution rose plot for the 1000- to 2000-ft morning box climb east of Texas City shows wind directions mostly from the west-southwest with ozone concentrations ranging from 19 to 61 ppb (Figure 6-5), similar to the other 1000- to 2000-ft box climbs. Again, on one day [August 22, 2000], the winds were from the east-northeast and ozone concentrations (54 ppb) were higher than average for the five days.
- The pollution rose plot for the 2000- to 5000-ft msl morning box climb east of Texas City shows wind directions ranging from the southwest to southeast (Figure 6-6). The plot shows that ozone concentrations were generally greater than the ozone concentrations for the 1000- to 2000-ft box climb.
- The pollution rose plot for the 1000- to 5000-ft msl afternoon box climb east of Texas City over Galveston Bay shows wind directions ranging from northwest through south to east (Figure 6-7), which are more variable than the morning plots. The afternoon plot shows slightly higher ozone concentrations (52 to 79 ppb) compared to the morning 1000- to 2000-ft box climb. However, these average layer concentrations are much lower than the peak ozone concentrations observed by the aircraft on any of the days analyzed.

7. CORRELATION BETWEEN OZONE AND SEVERAL PRIMARY POLLUTANTS

7.1 PURPOSE

The principal goal of the correlation analysis was to understand the co-variation of ozone with NO_y, indicative of the precursor NO_x, and with the primary pollutants SO_2 and CO, which can lend insight into the sources of the observed NO_x. Scatter plots of ozone vs. NO_y, ozone vs. CO, and ozone vs. SO_2 are presented for each flight. A description of the data plots and several example plots, including a scatter plot of SO_2 vs. NO_y, are provided in Section 7.2. The SO_2 vs. NO_y scatter plot contains lines representative of expected emission ratios from a variety of point and mobile sources, which allows a qualitative analysis of the source types that have contributed NO_x to a particular air mass. Plots for all of the flights are contained in Appendix A.

7.2 DESCRIPTION OF DATA PLOTS

7.2.1 Ozone Correlations

Scatter plots of ozone vs. NO_y, SO_2, and CO are useful for several purposes. First, ozone vs. NO_y provides a measure of the ozone production efficiency per NO_x for a given air mass. Correlation of ozone with SO_2 and CO lends insight into the source type that provided the NO_x, where correlation with SO_2 suggests a variety of point source types and correlation with CO suggests a contribution from mobile sources. It is important to note that the CO instrument used during the study was not properly calibrated and quantitative data were unattainable. However, for the flights during which the CO instrument was operated, the instrument did respond to changes in CO concentration. The ozone vs. CO scatter plots shown in this report rely upon normalized CO data, which is characterized by a mean of 0 and a standard deviation of 1. For each flight, all of the observed data for these species are plotted on a panel containing the three plots. An example of these three plots is shown in **Figure 7-1**, along with an SO_2 vs. NO_y plot (described in Section 7.2.2). The air parcels observed during the represented flight showed a strong correlation between ozone and each of the three primary pollutants, indicating contributions from both point and mobile sources. This is supported by the fact that data points lie along both the point source and mobile source emission ratio lines in the SO_2 vs. NO_y plot.

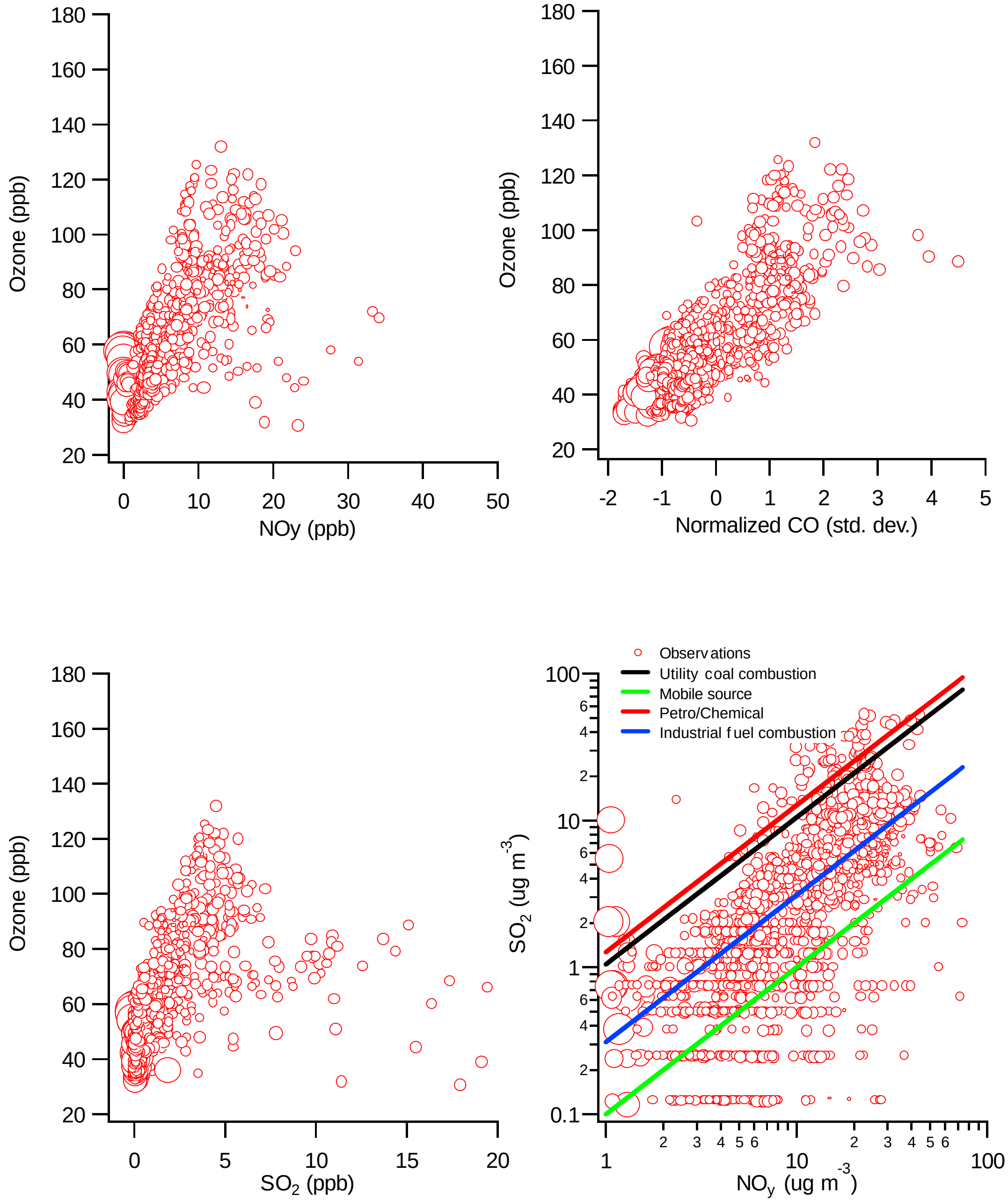


Figure 7-1. Example scatter plots used to examine the correlation between ozone and several primary pollutants. The data shown here were collected on flight number 141b, conducted on August 26, 2000. The symbol size is proportional to the altitude where the data was collected. The smallest symbol represents data collected below 300 m, and the largest symbol indicates data collected at or above 1500 m. The data plotted are 10-second average values.

7.2.2 Emission Ratio

In addition to the ozone correlation scatter plots, an emission ratio scatter plot of SO_2 vs. NO_y is presented for each flight. In these plots, the data are presented as concentrations (ug/m^{-3}) rather than the standard mixing ratio, so that the observed ratios can be compared with expected mass emission ratios. The data are plotted on a log-log scale and lines are added to the plot that indicate the expected SO_x/NO_x emission ratio for a variety of important sources in the Houston region. The emission ratios indicated on the plot are shown in **Table 7-1** (from Radian Corporation, 1995). The purpose of plotting the data on a log-log scale is that the various emission ratios appear as a series of parallel lines (see Figure 7-1, bottom right panel). Observations from an air parcel strongly impacted by a given source type will tend to follow that ratio line for that source. There are several caveats that must be considered in connection with this type of analysis. First, if the atmospheric lifetime of the two species plotted are substantially different, the observations will tend away from the source ratio as the air parcel ages. A good example of this is CO (Lifetime = ~1 month) and NO_y (lifetime = ~1 day). The data presented here for SO_2 and NO_y are well suited for this analysis, since both have a lifetime of about 1 day. Second, a given air parcel may be impacted by more than one source type by the time the observations are made, which tends to move the data points somewhere in between the two constant ratio lines. Finally, the expected emission ratios may not represent the actual emission ratio from a given source, but from a mixture of different sources close together. This type of analysis can be useful for evaluating the accuracy of the expected emission ratios where observations of sufficient precision are collected. In practice, the emission ratio scatter plot provides a qualitative measure of the source types that impacted a given air parcel, or group of air parcels.

Table 7-1. Expected emission ratios from several major source types in the state of Texas.[1]

Source Type	SO_x/NO_x emission ratio	CO/NO_x emission ratio
Utility coal combustion	1.05	0.05
Mobile sources	0.10	6.69
Industrial and commercial fuel combustion	0.31	0.16
Petroleum and other chemical production	1.27	1.93

[1] From Radian Corporation, 1995

7.3 DISCUSSION

7.3.1 Ozone Correlations

Because all of the data from a given flight are presented on one plot, there are typically several different air mass types represented. Characterization of these air masses varies from fresh emissions to photochemically aged emissions. Correlation between ozone and these primary pollutants is observed in the photochemically aged air masses, while anti-correlation is typically observed in air masses characterized by fresh emissions. The data presented in Figure 7-1 show a correlation between ozone and each of the three primary pollutants, indicating that both point and mobile sources contributed to the ozone produced. In addition, there are data points in both the NO_y and SO_2 plots that show little or no correlation with the observed ozone. The lack of corresponding data points in the CO plot suggests that these data represent impact from a point source. For other flights, there are instances where CO and NO_y showed excursions independent of SO_2, which is consistent with impact from fresh mobile emissions. The correlation observed between ozone and the primary pollutants was observed most of the time in the afternoon flights, which were conducted near the peak of photochemical activity. Correlation between ozone and the primary pollutants was also observed in some of the morning flights, due in part to residual, photochemically aged air masses encountered in the aloft layers. There are also some morning flights wherein ozone showed no correlation with moderately high concentrations of the primary pollutants; this is indicative of fresh emissions.

The slope observed between ozone and NO_y has been used as a qualitative measure of the ozone production efficiency per emitted NO_x. For those flights where photochemical production of ozone was evidenced by a correlation between ozone and NO_y, the ozone/NO_y slope was estimated. That value, along with a qualitative indicator of whether the observations exhibited characteristics of photochemical activity, fresh emissions, or both, is shown for each flight in **Table 7-2**.

All of the afternoon flights and a couple of the morning flights exhibited photochemical ozone production. All except one of the flights showed evidence of fresh emissions. The approximate ozone/NO_y slope varied from 3 to 10, possibly depending on the source type that had the greatest impact on the air parcel. The observations that were more strongly impacted by the point sources of pollution tended to have lower ozone production rates.

Table 7-2. Qualitative summary of emission sources and ozone production observed during selected flights.

Page 1 of 2

Flight date	Flight number	Photochemical activity observed	Fresh emissions observed	Point source impact	Mobile source impact	Approximate ozone/NO_y ratio
08/08/00	132	No	Yes	Yes	Yes	---
08/18/00	135	Yes	Yes	Yes	Yes	6
08/19/00	136a	No	Yes	Yes	Yes	---
08/19/00	136b	Yes	Yes	Yes	Yes	8
08/21/00	137a	No	Yes	Yes	Yes	---
08/21/00	137b	Yes	Yes	Yes	Yes	5-7
08/26/00	141a	No	Yes	Yes	Yes	---
08/26/00	141b	Yes	Yes	Yes	Yes	3-10

Table 7-2. Qualitative summary of emission sources and ozone production observed during selected flights.

Flight date	Flight number	Photochemical activity observed	Fresh emissions observed	Point source impact	Mobile source impact	Approximate ozone/NO_y ratio
08/28/00	142	No	Yes	Some	Yes	---
08/29/00	143a	No	Yes	Yes	Yes	---
08/29/00	143b	Yes	Yes	Yes	Some	2-8
08/30/00	144a	No	Yes	Yes	Some	---
08/30/00	144b	Yes	Yes	Yes	Some	3
09/01/00	145a	Yes	Yes	Yes	Some	3
09/01/00	145b	Yes	Yes	Yes	Some	3.5
09/03/00	146	Yes	Yes	Yes	Some	5
09/04/00	147a	Yes	Yes	Yes	Yes	8
09/04/00	147b	Yes	Yes	Yes	Yes	7
09/05/00	148	Yes	No	Yes	Yes	9
09/12/00	150a	No	Yes	Yes	Yes	---
09/12/00	150b	Yes	Yes	Yes	Yes	5

7.3.2 Emission Ratio Scatter Plots

The observed emission ratios were consistent with the conclusion that mobile sources impacted air parcels to some extent on all of the flights. At the same time, all but one of the flights included observations consistent with impact from point sources. With few exceptions, the expected emission ratios bracketed the observations quite well. The greatest deviation was at low SO_2/NO_y ratios near the expected mobile source ratio. This can be understood to some extent by the fact that emission ratio used, SO_2/NO_y=0.1, represents all mobile sources. The expected ratio for light-duty, gasoline-powered vehicles that may have dominated the source category is 0.05. The lower ratio would show better agreement with some of the observations.

Ideally, the SO_2/NO_y analysis would be compared with a similar analysis using the CO/NO_y ratio. Unfortunately, the quality of the CO data collected during the study was not of adequate accuracy to permit its use for this application.

7.4 SUMMARY

- Evidence of photochemical ozone production was observed on all of the afternoon flights and some of the of the morning flights, with production rates ranging from 3 to 10 ppbv ozone per ppbv NO_y.
- The correlation of ozone with CO and with SO_2 is consistent with contributions of NO_x from both point and mobile sources.

- Ozone production rates tended to be lower in air parcels that showed greater contribution from point sources.
- Analysis of observed and expected emission ratios was consistent with both point and mobile sources contributing significant NO_x to the air parcels observed in all but one of the flights.

8. RECOMMENDATIONS

This document contains a review of the data collected during 20 Baylor aircraft flights conducted in summer 2000. The purpose of this review was to describe and display the ozone, NO, NO_y, and SO_2 data and to address some technical questions regarding ozone pollution in the Houston–Galveston Bay area. Although this review utilized meteorological and surface air quality data collected by other sources, there are still data collected by the Baylor aircraft and by other organizations during TexAQS 2000 that were not included in this review. In addition, other analyses of data collected during TexAQS 2000 have been or are being performed by other organizations. In this section we suggest some additional analyses that would build on the findings presented in this report and take advantage of other data and analyses to develop a more comprehensive understanding of air quality in the Houston–Galveston Bay area.

Several 2000 ozone episodes are under considerations or have already been selected for three-dimensional photochemical modeling of the Houston–Galveston Bay area. To replicate the atmospheric physical and chemical processes in models, it is necessary to have a detailed understanding and characterization of the temporal and spatial distribution of air quality and meteorology on the days being modeled. Therefore, a detailed analysis and characterization of available meteorological and air quality data, including the data presented in this report, should be performed for the selected modeling days.

Radar profiler wind data from Ellington Field, EDAS model data, and satellite images were used to characterize the flow patterns in the Houston–Galveston. Since the flow patterns in the Houston–Galveston Bay area are complex, the radar profiler wind data at only one site are probably not representative of the flow patterns throughout the area. In addition, the resolution of the EDAS model data (40 km) is probably too coarse to resolve the spatial and temporal flow patterns. A more accurate characterization of the flow patterns could be made by including Sodar data and radar profiler wind data collected at other sites in the area. The results from these analyses could then be used to support modeling efforts.

The spatial and temporal distributions of ozone, NO_y, NO, and SO_2, for 20 flights were characterized. In 2000, the Baylor aircraft also collected VOC canister data. However, these data were not reviewed because the data were not readily available at the time of this analysis. In addition, VOC data were collected at surface sites operated by TNRCC and the Houston Regional Monitoring Network and in other aircraft. Because VOCs are a key ingredient in ozone formation, it is important to characterize both the concentrations and composition of the VOCs in the context of the other data.

In this analysis, aloft ozone data collected by the Baylor aircraft were used to characterize the three-dimensional distribution of ozone. Although the data worked quite well for this purpose, additional information could be gained by analyzing aloft ozone data collected by other aircraft and by Lidar. The Lidar provides continuous profiles of ozone at one location, so a time-history of vertical ozone profiles can be determined. The time-history of ozone profiles could be used in conjunction with upper air wind data could better characterize the vertical ozone distribution in relation to the Land, Bay, and Gulf Breezes.

Several distinct layers of ozone, NO_y, NO, and SO_2 concentrations were observed during the morning and afternoon flights. Using emissions data and additional upper-air and surface-wind data, an attempt should be made to attribute these pollutant layers to specific sources, groups of sources, or source areas.

Wind data collected by the Baylor aircraft were compared to wind data collected by the Ellington Field radar wind profiler. It was determined that the aircraft wind data, at times, compared poorly with the profiler wind data. However, there were times when the two data sets compared well. Therefore, a more detailed validation of the aircraft data should be performed so that the final data set contains only valid data that can be used in analyses.

This analysis was performed without review or integration of other analyses performed, or being performed, by various organizations such as TNRCC, National Oceanic and Atmospheric Administration, National Center for Atmospheric Research, Texas A & M, University Texas at Austin, Rice University, Brookhaven National Lab, and Baylor University. A review and integration of the analysis performed by these groups with this analysis would provide a more complete understanding of the air quality in the Houston–Galveston Bay area.

9. REFERENCES

Dye T.S., Lindsey C.G., and Anderson J.A. (1995) Estimates of mixing depth from "boundary layer" radar profilers. Preprints from *the 9th Symposium on Meteorological Observations and Instrumentation, Charlotte, NC, March 27-31*, STI-94212-1451, pp. 156-160.

MacDonald C.P., Blumenthal D.L., Roberts P.T., and Crews J.M. (2001) Analysis of 1997 through 1999 air quality data collected by the Baylor University aircraft. Report prepared for the Texas Natural Resource Conservation Commission, Austin, TX by Sonoma Technology, Inc., Petaluma, CA, STI-900510-2033-FR, January.

Radian Corporation. (1995) An emissions inventory for assessing regional haze on the Colorado Plateau. Report prepared by the Radian Corporation, January.

Suffern M., Alvarez S., Begbie J, Tilghman M, Zanin G., Shauck M. (2000) Airborne Pollution Monitoring Services Year 2000 Executive Summary, Central States Air Resource Agencies (CenSARA). Draft report prepared for the Texas Natural Resource Conservation Commission by Baylor University Aviation Sciences Department, Renewable Aviation Fuels Development Center, Contract Number 582-9-00782, December.

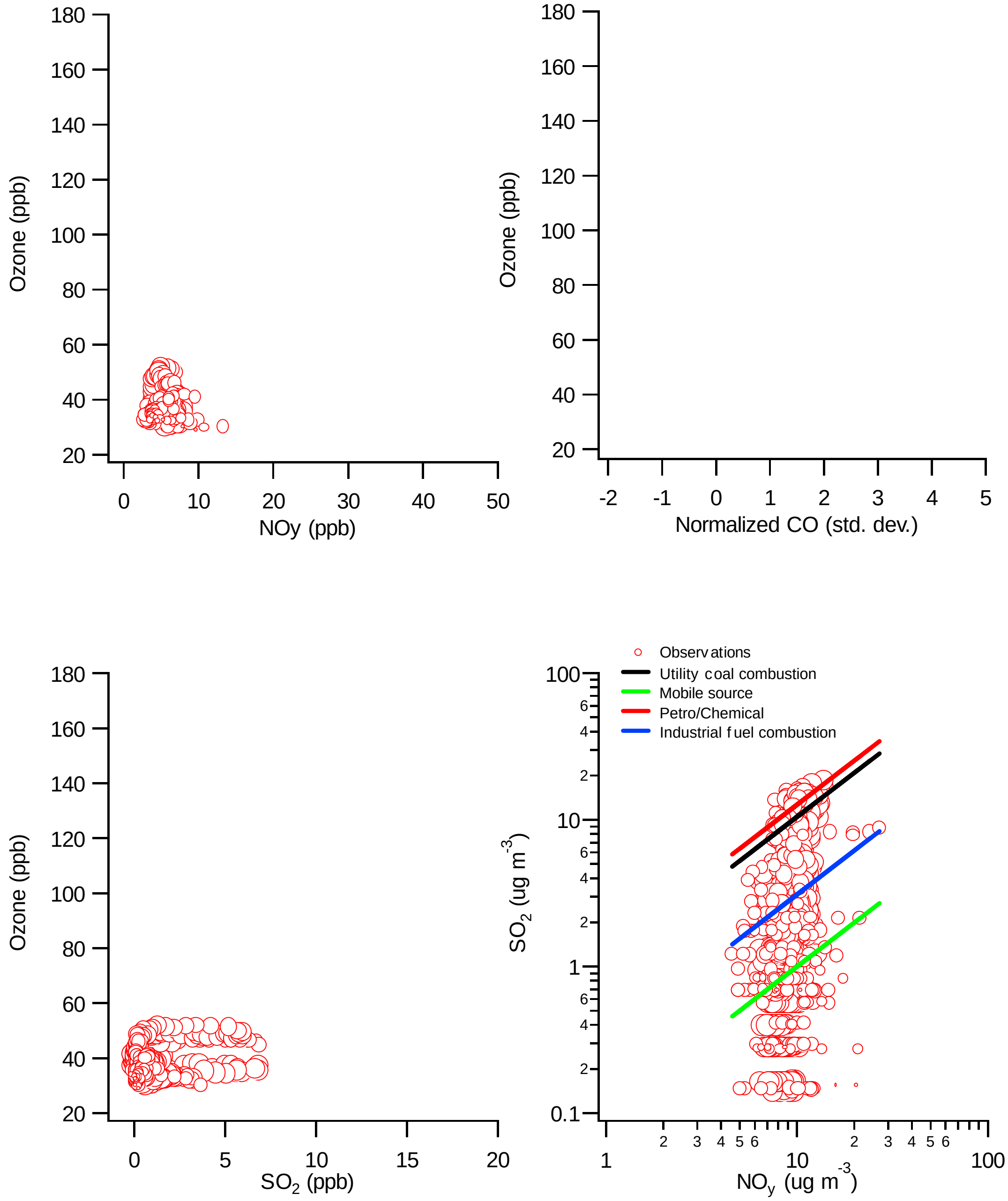
White A.B., Fairall C.W., and Wolfe D.E. (1991) Use of 915 MHz wind profiler data to describe the diurnal variability of the mixed layer. In Preprints from the *AMS and A&WMA 7th Joint Conference on Applications of Air Pollution Meteorology, New Orleans, LA January 14-18,* American Meteorological Society, Boston, MA.

Wyngaard J.C. and LeMone M.A. (1980) Behavior of the refractive index structure parameter in the entraining convective boundary layer. *J. Atmos. Sci*. **37**, 1573-1585.

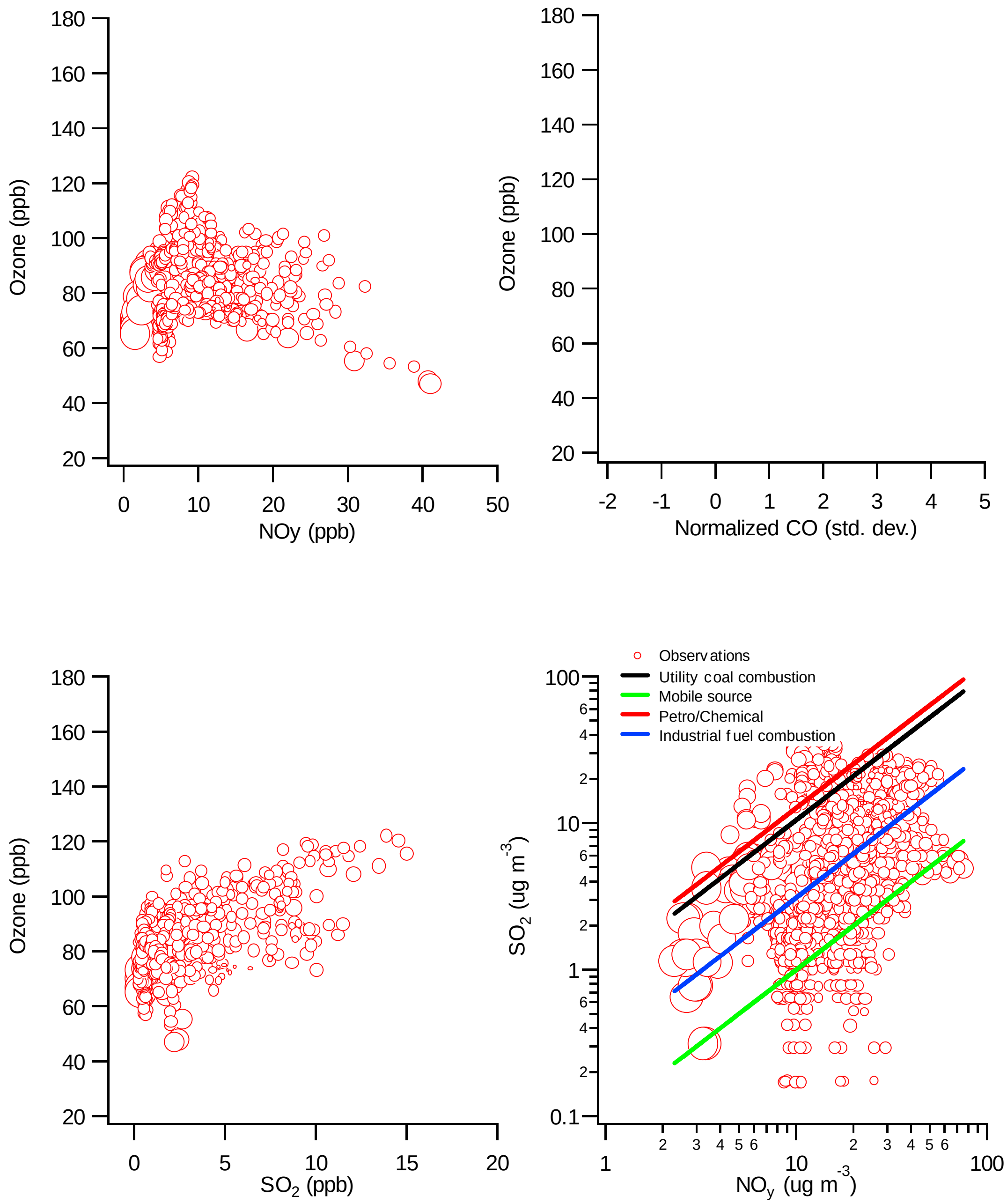
APPENDIX A

CORRELATION OF OZONE WITH SEVERAL PRIMARY POLLUTANTS

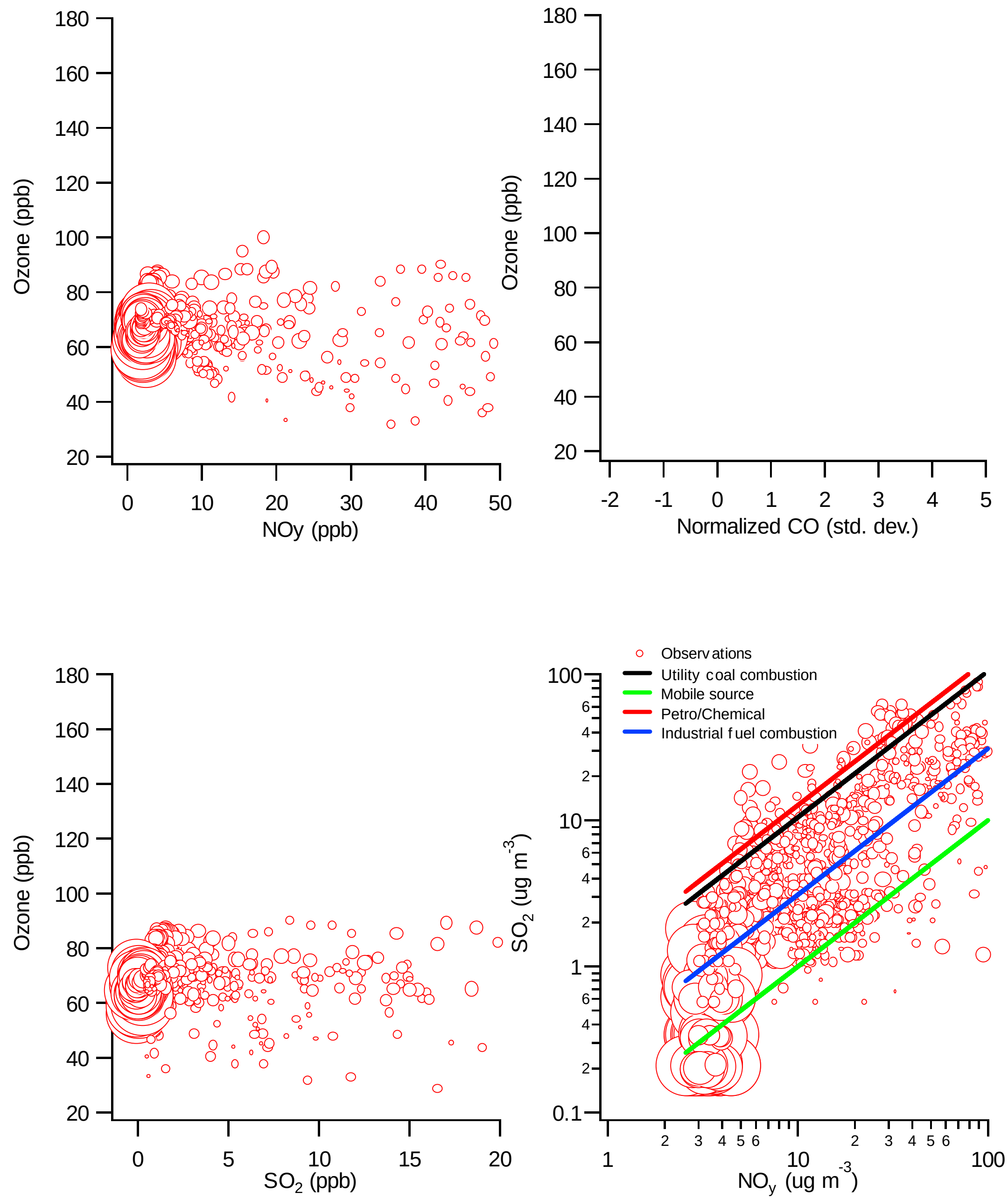
This appendix contains scatter plots of ozone vs. NO_y, CO, and SO_2, and SO_2 vs. NO_y for each of the flights conducted by the Baylor University Twin Otter aircraft in and around Houston, Texas during the TexAQS 2000. The importance and interpretation of these scatter plots are discussed in Section 7 of the final report. At the bottom of each panel the data file used to produce the plots is indicated in the format "VCATSYYMMDD.eng", where YYMMDD indicates the date of the flight. Where two flights were performed on a single day, an "a" (morning flight) or a "b" (afternoon flight) is appended after the date.



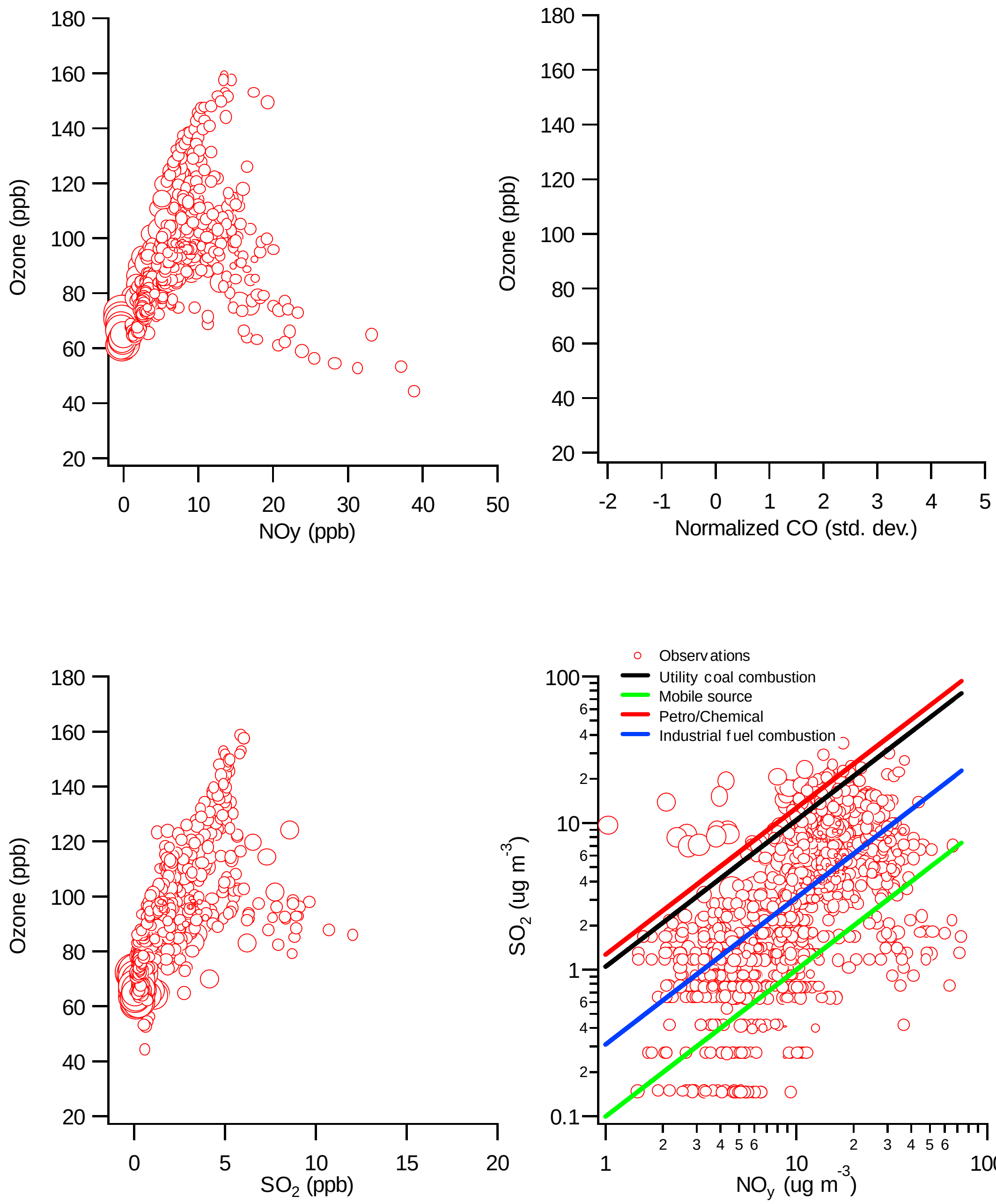
Data file: VCATS000808.eng



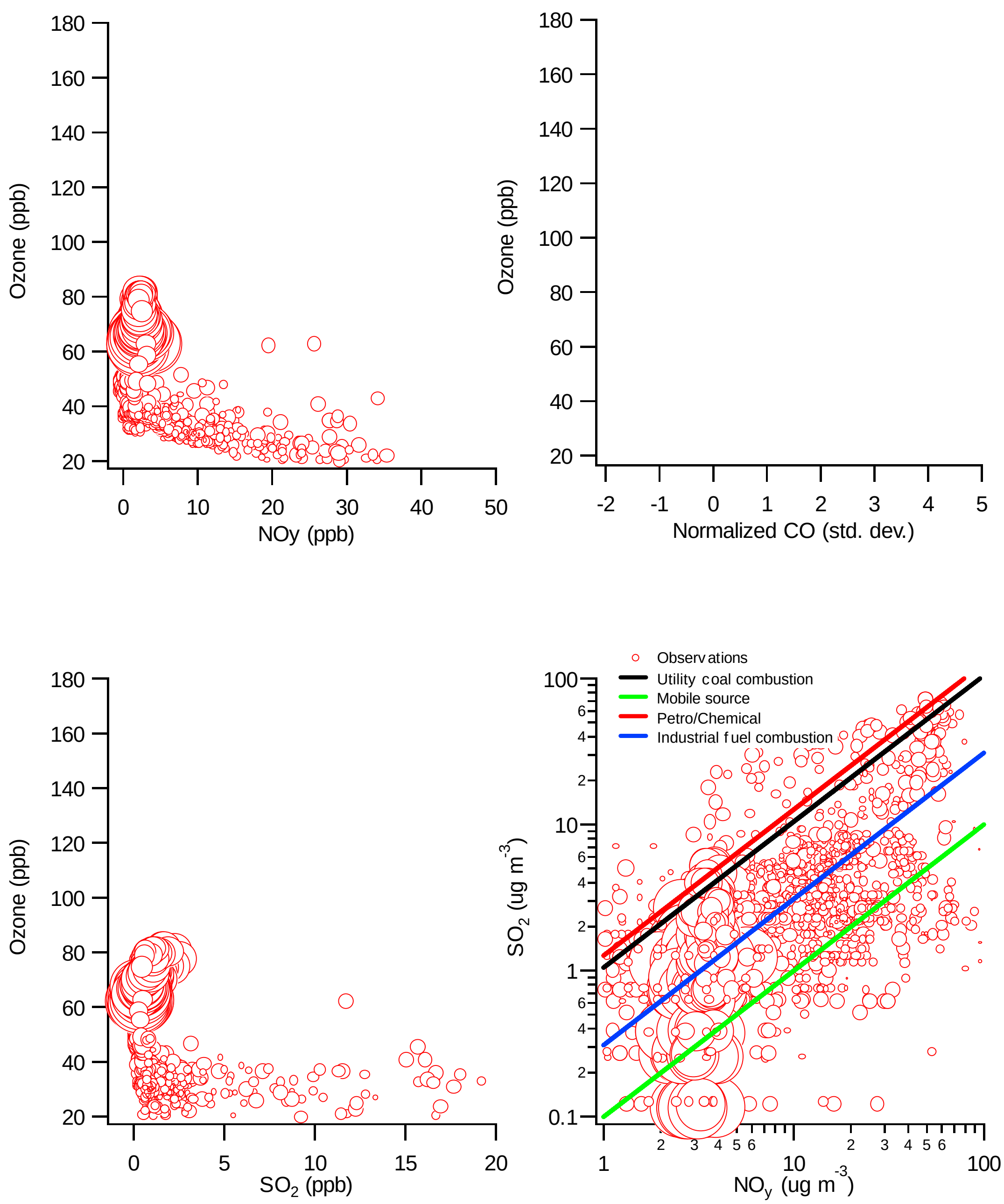
Data file: VCATS000818.eng



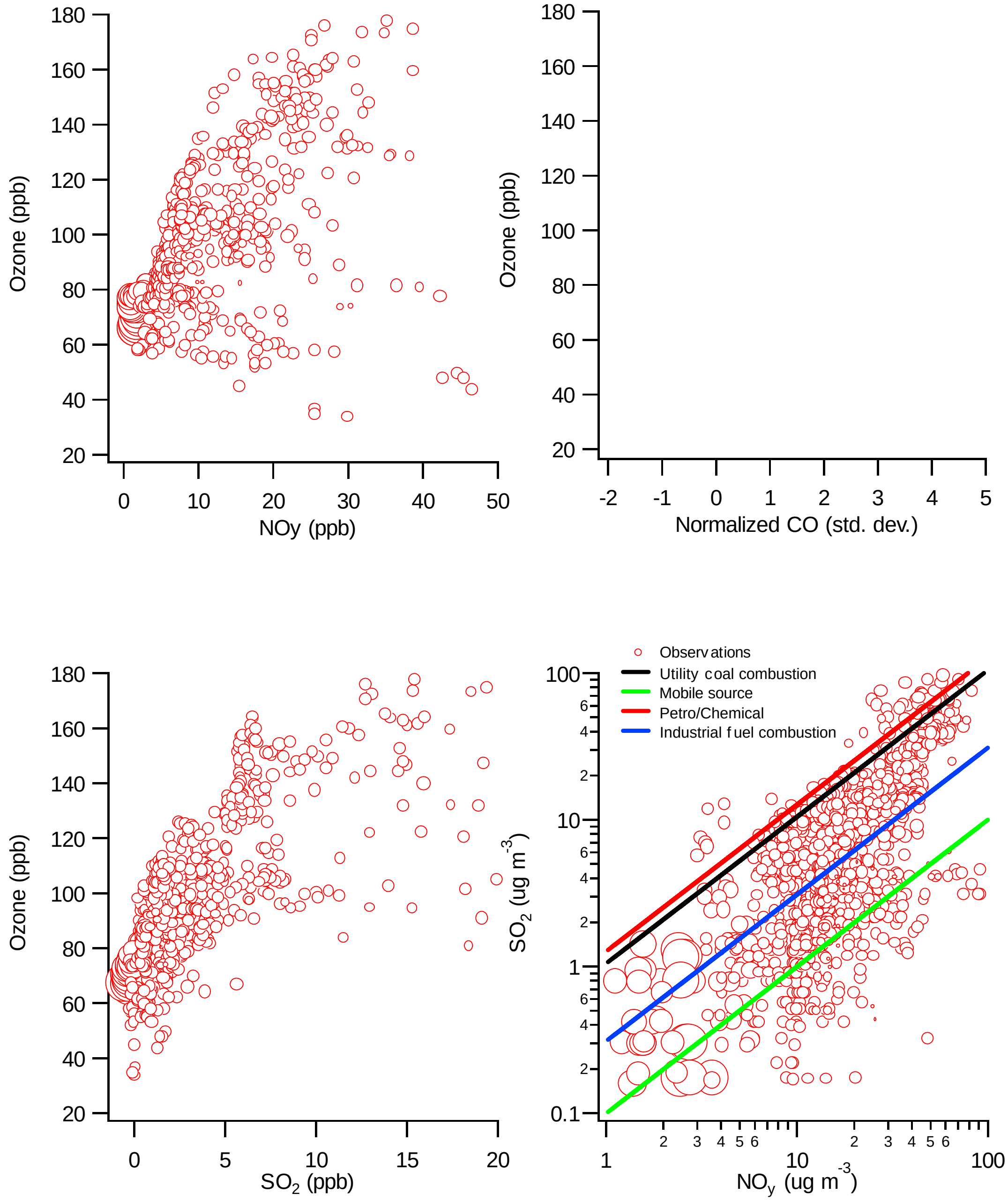
Data file: VCATS000819a.eng



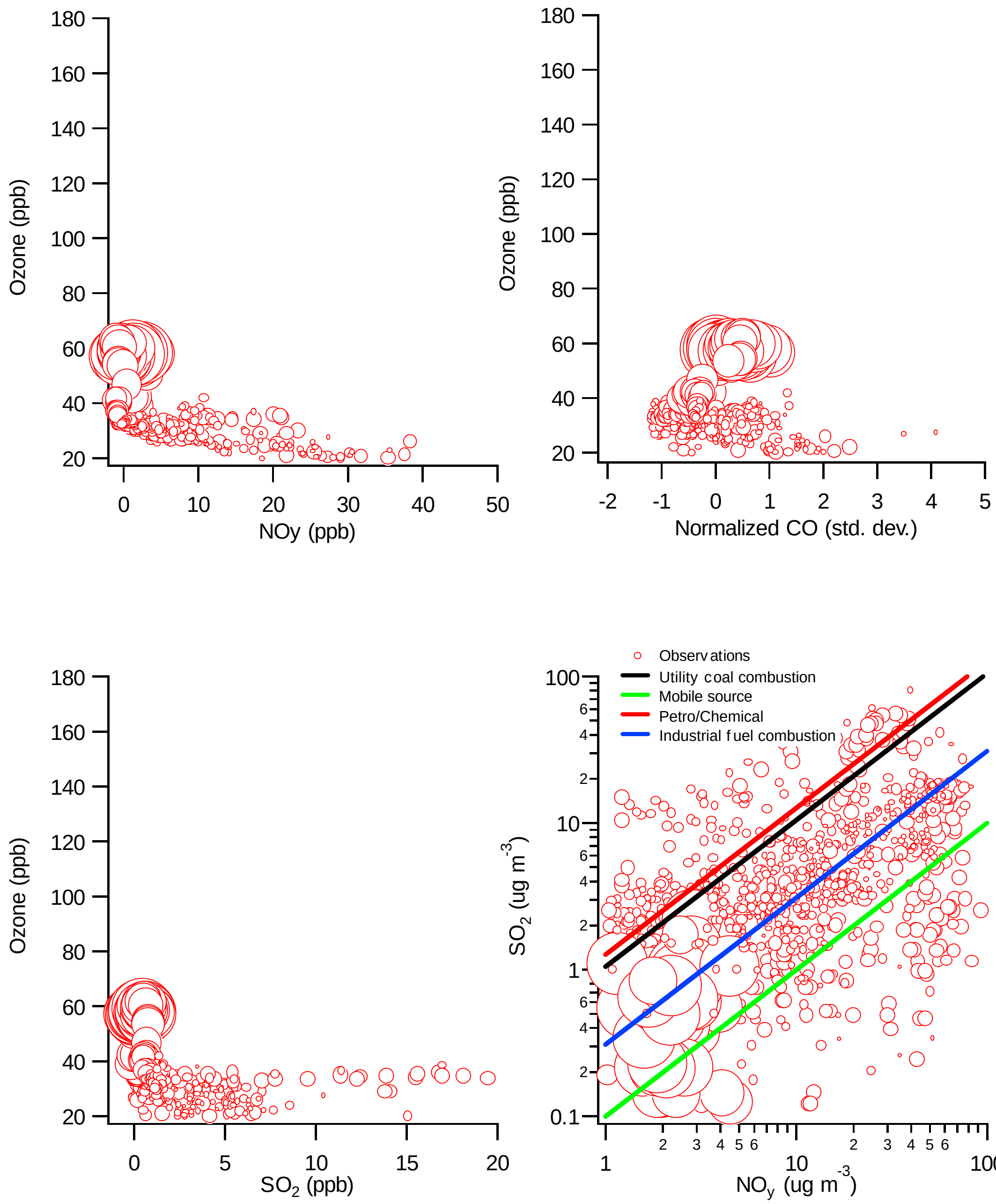
Data file: VCATS000819b.eng



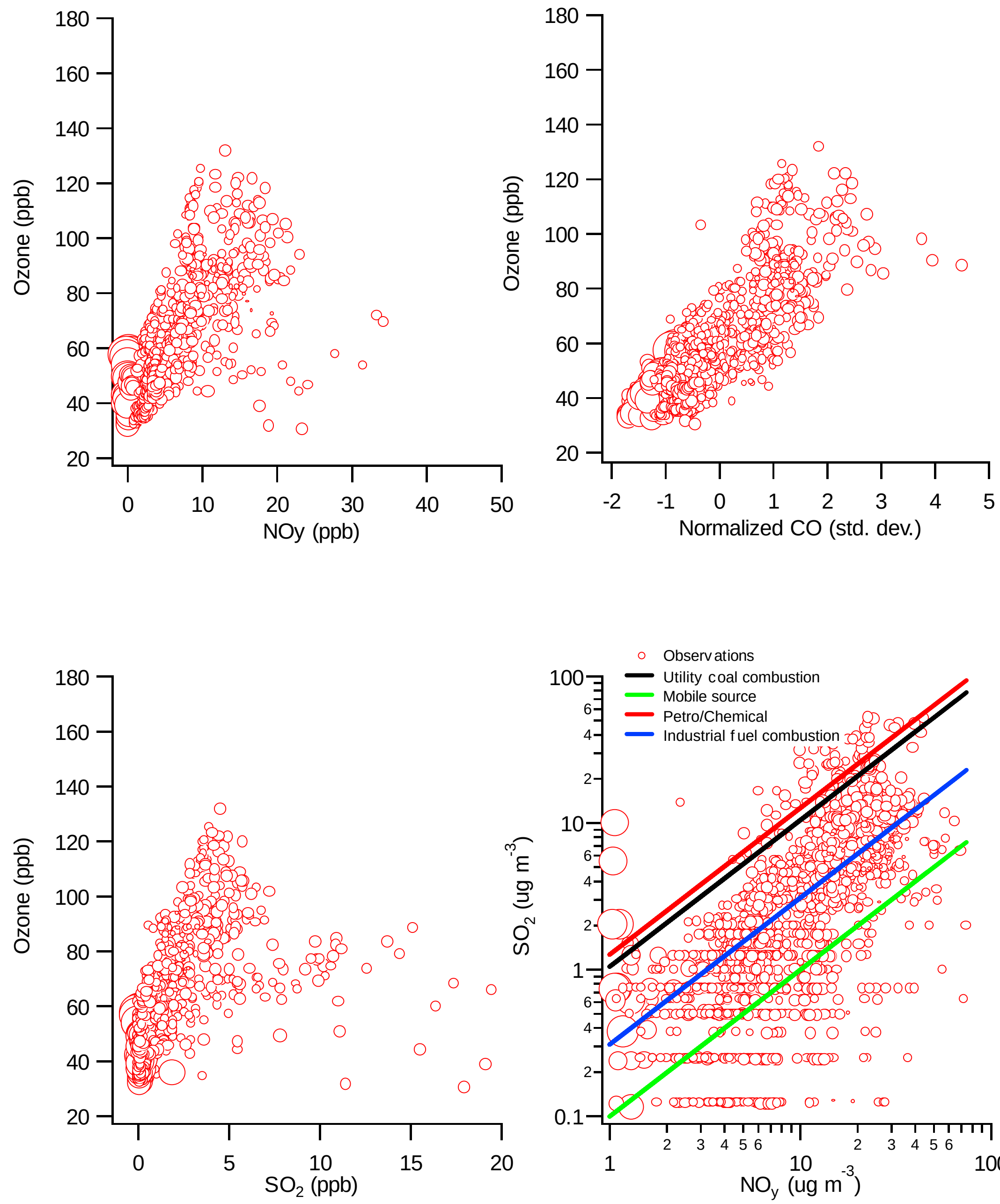
Data file: VCATS000821a.eng



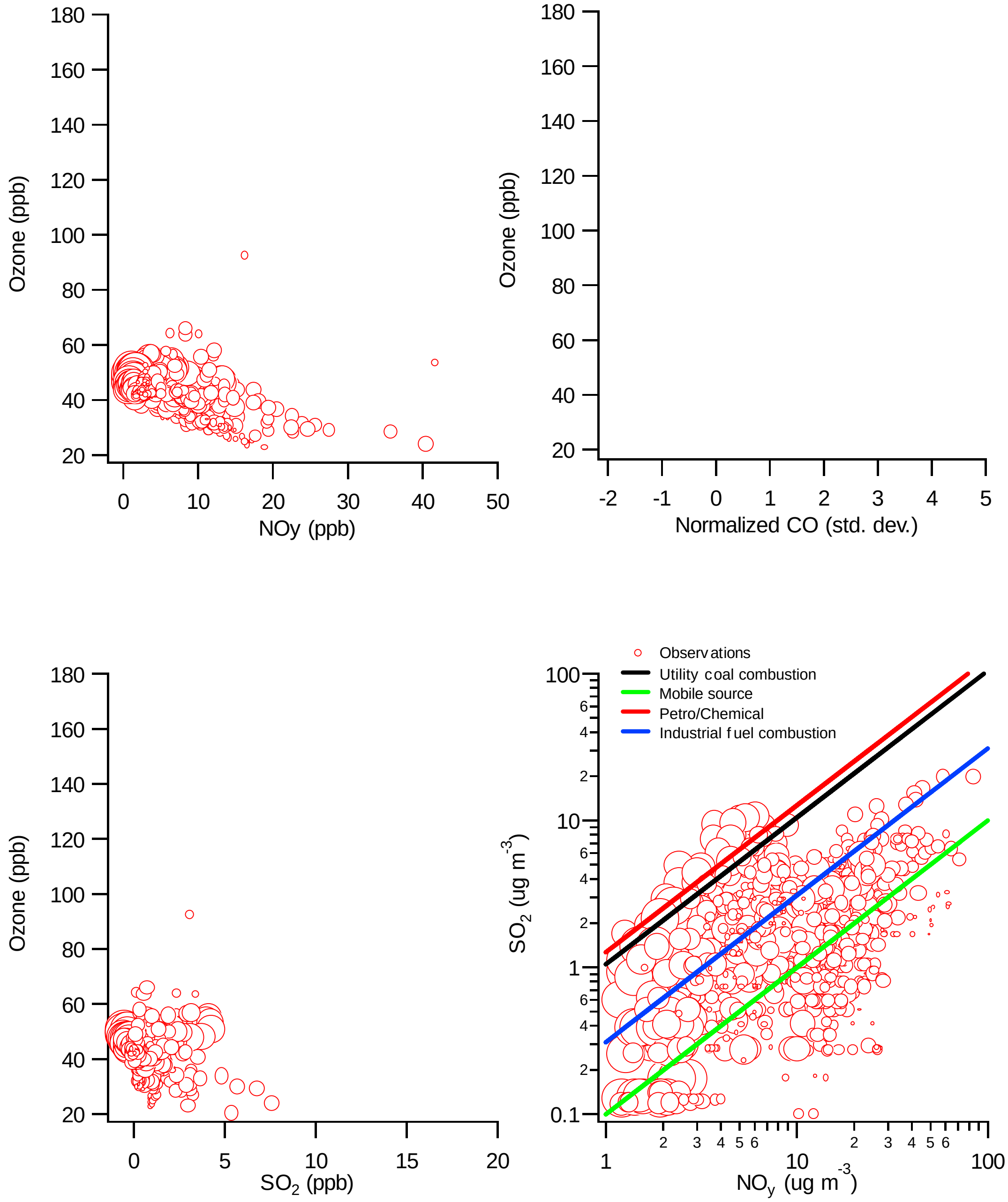
Data file: VCATS000821b.eng



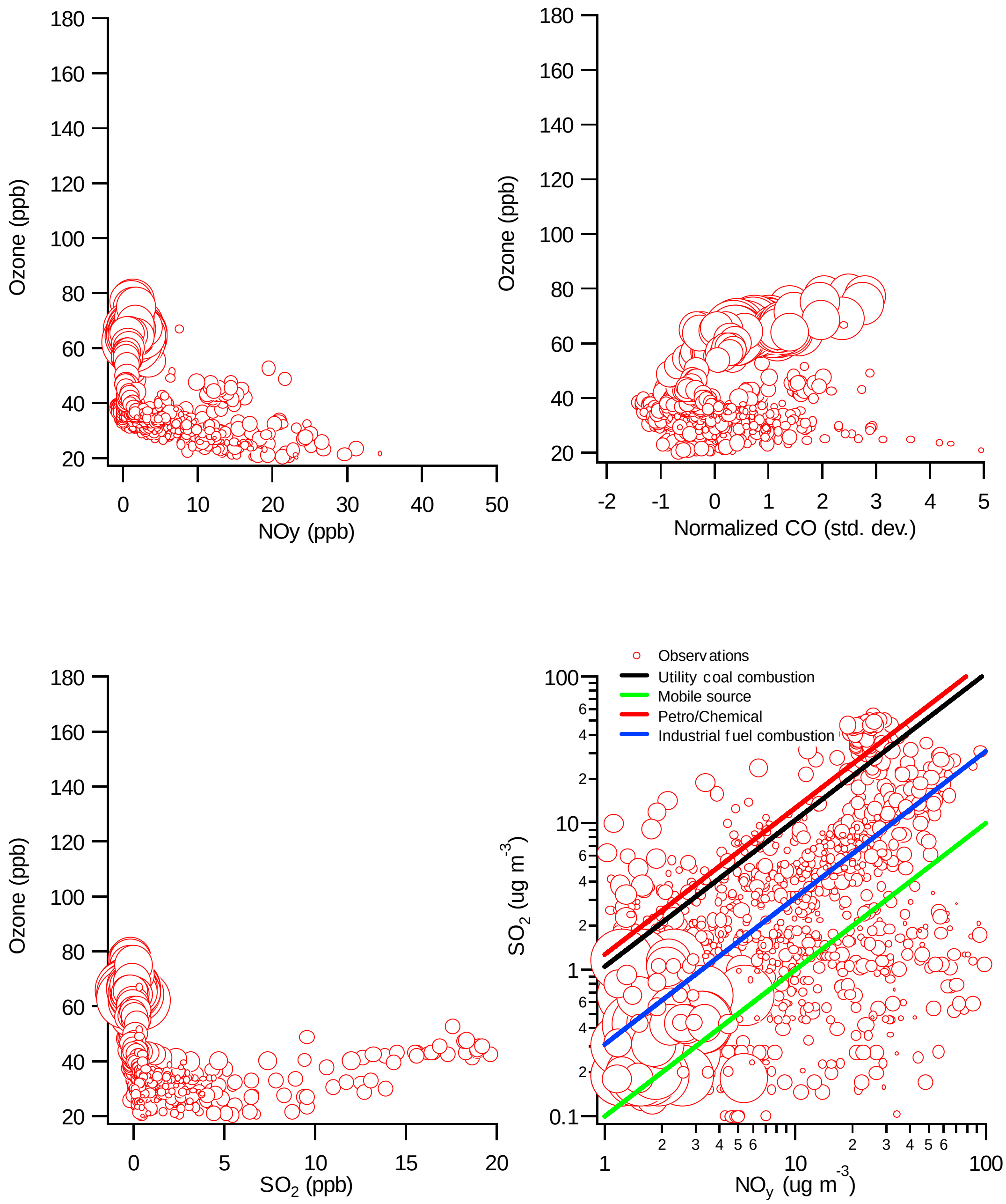
Data file: VCATS000826a.eng



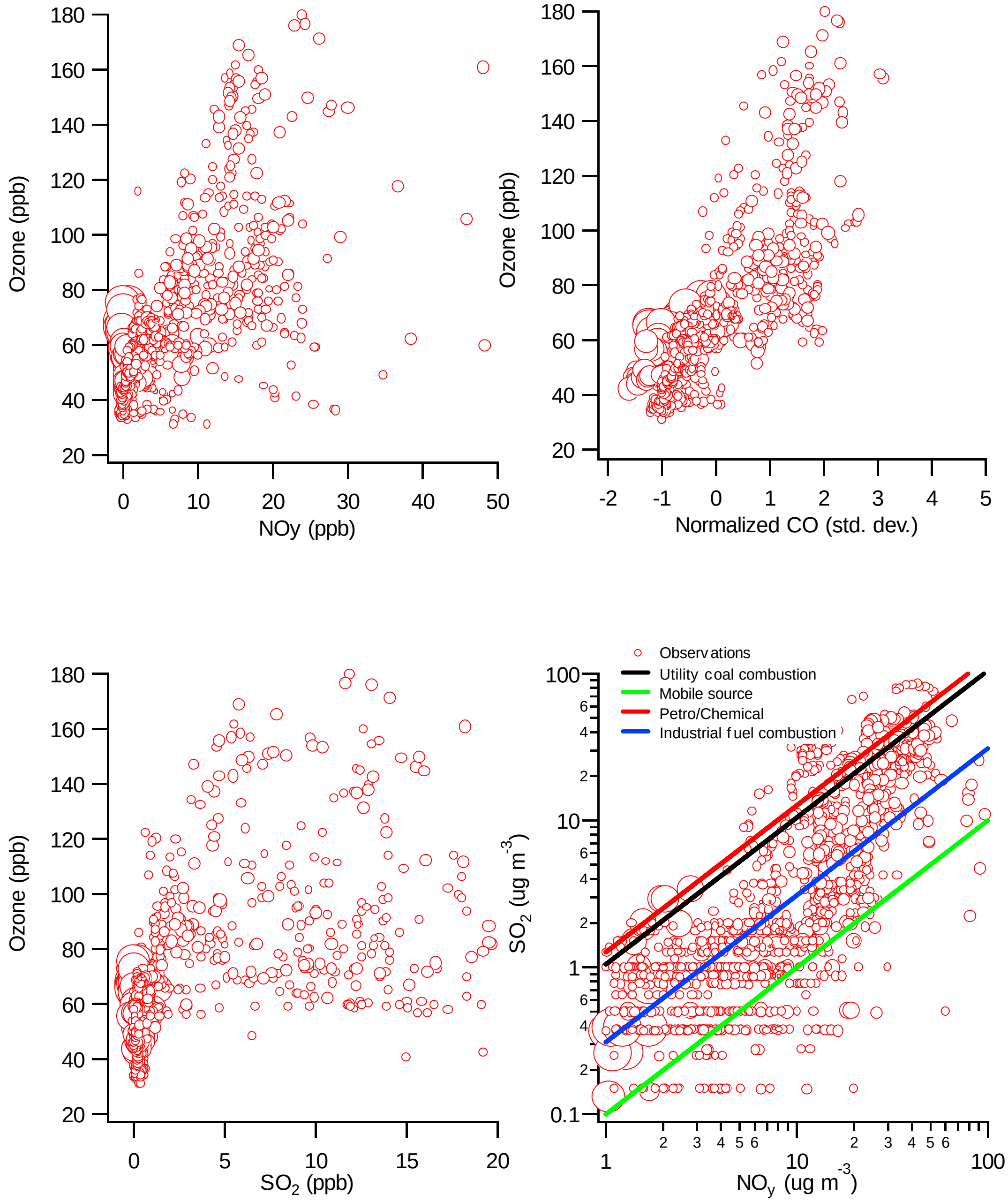
Data file: VCATS000826b.eng



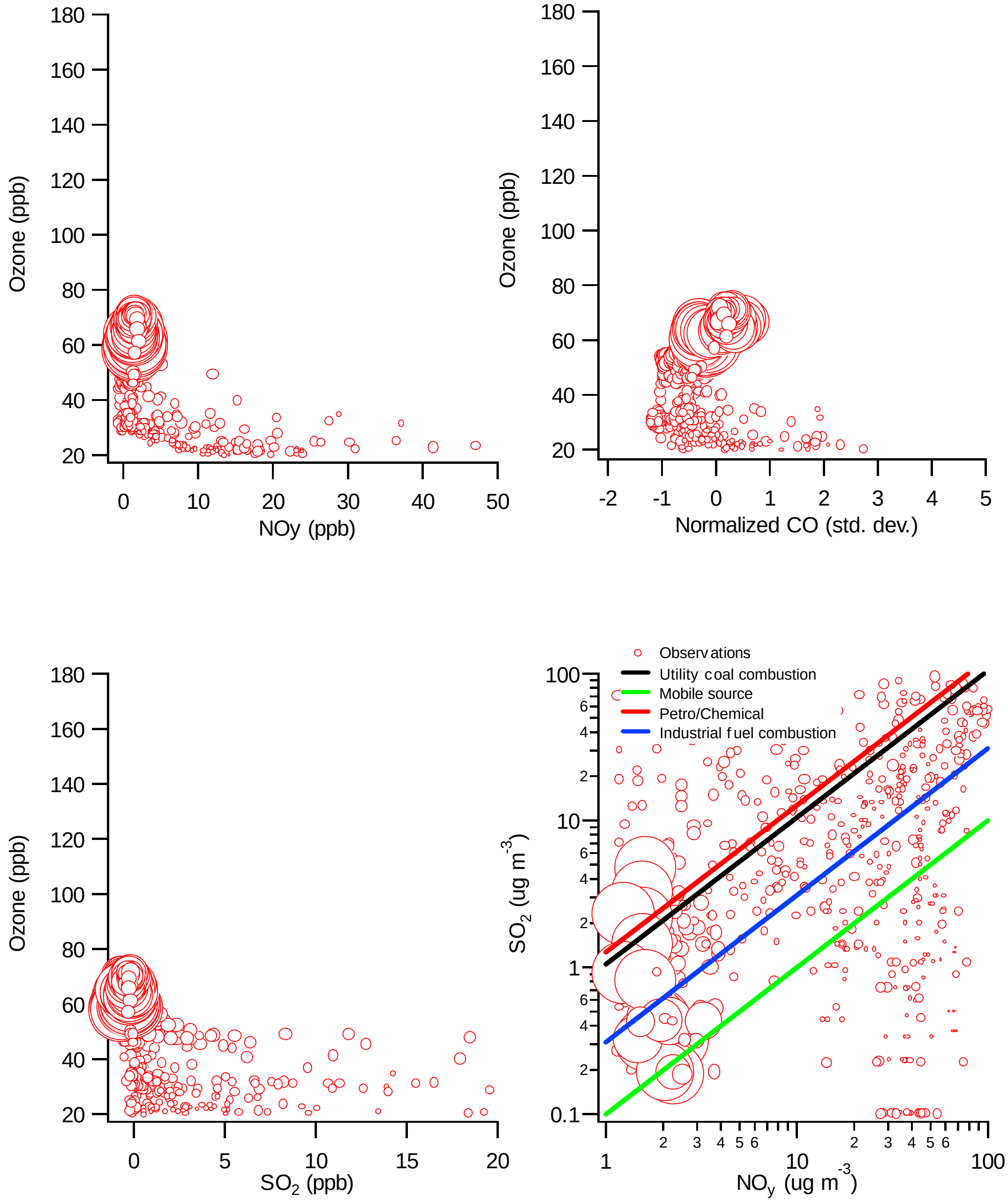
Data file: VCATS000828a.eng



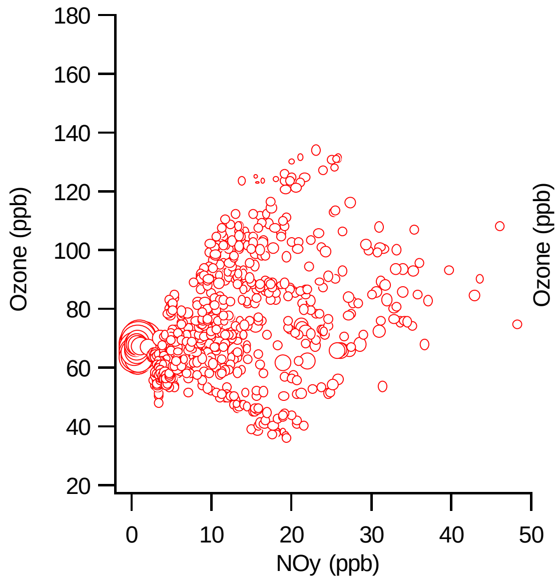
Data file: VCATS000829a.eng

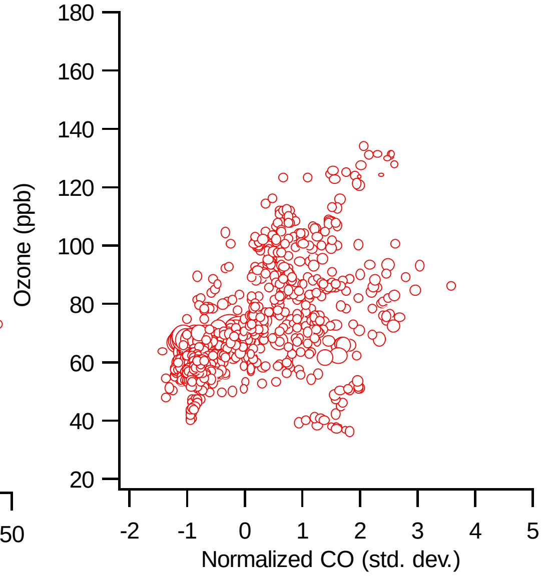


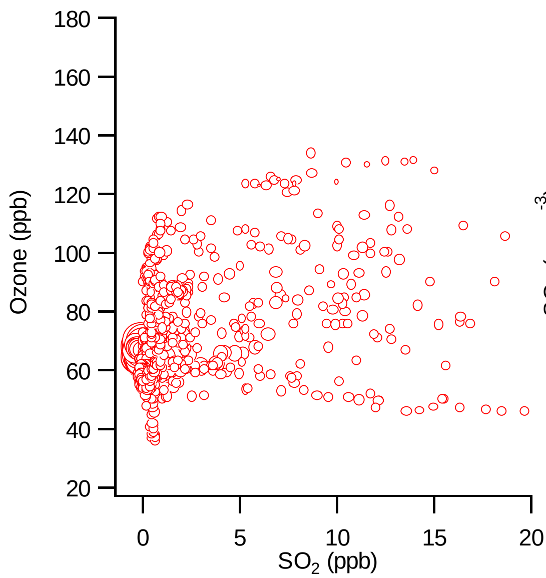
Data file: VCATS000829b.eng

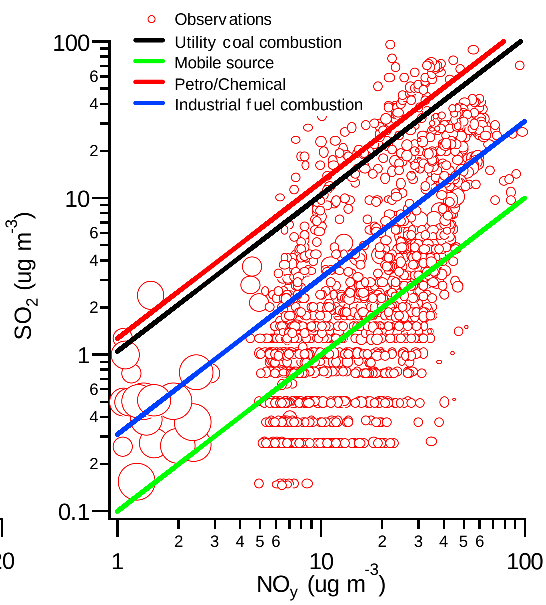


Data file: VCATS000830a.eng

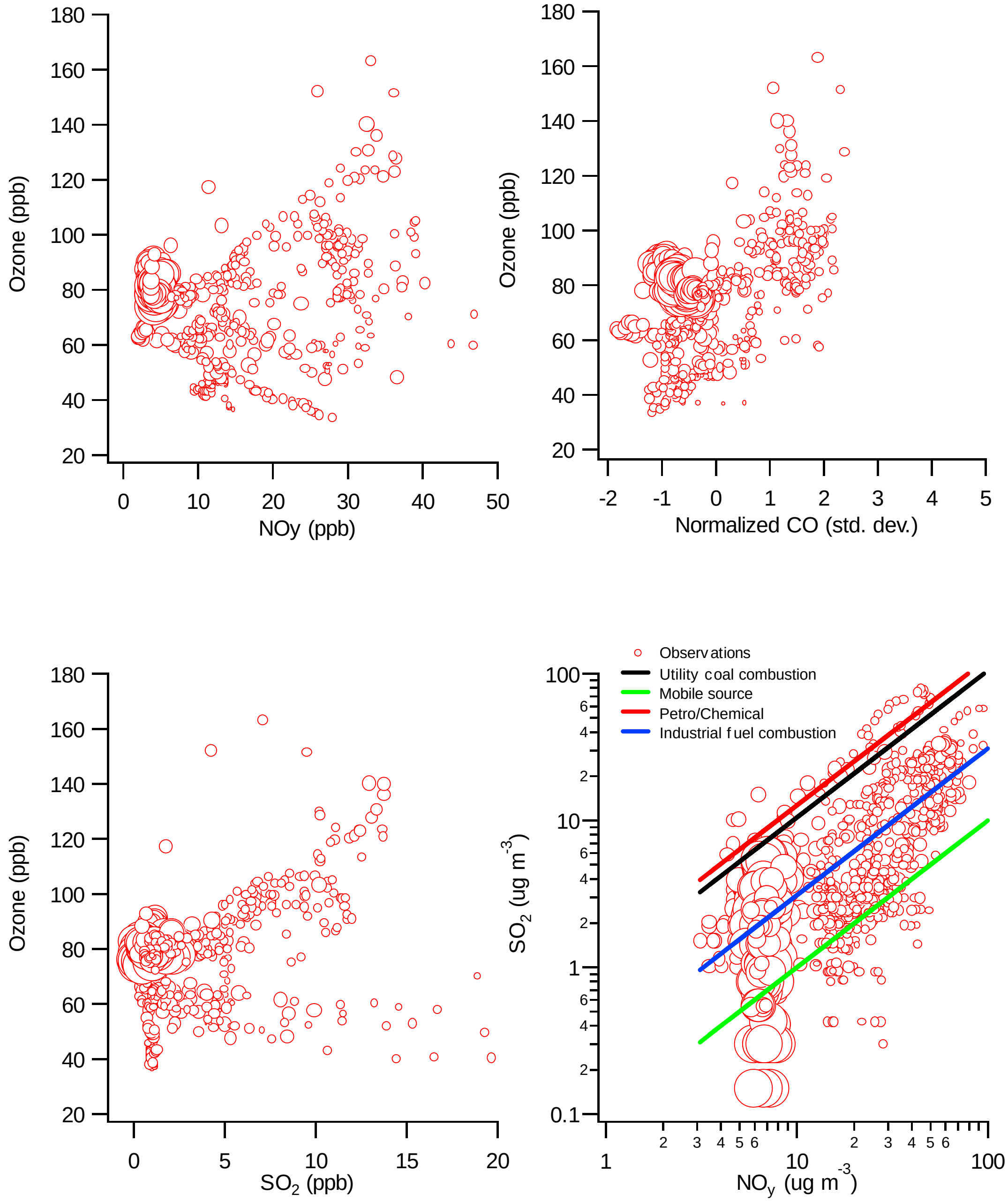




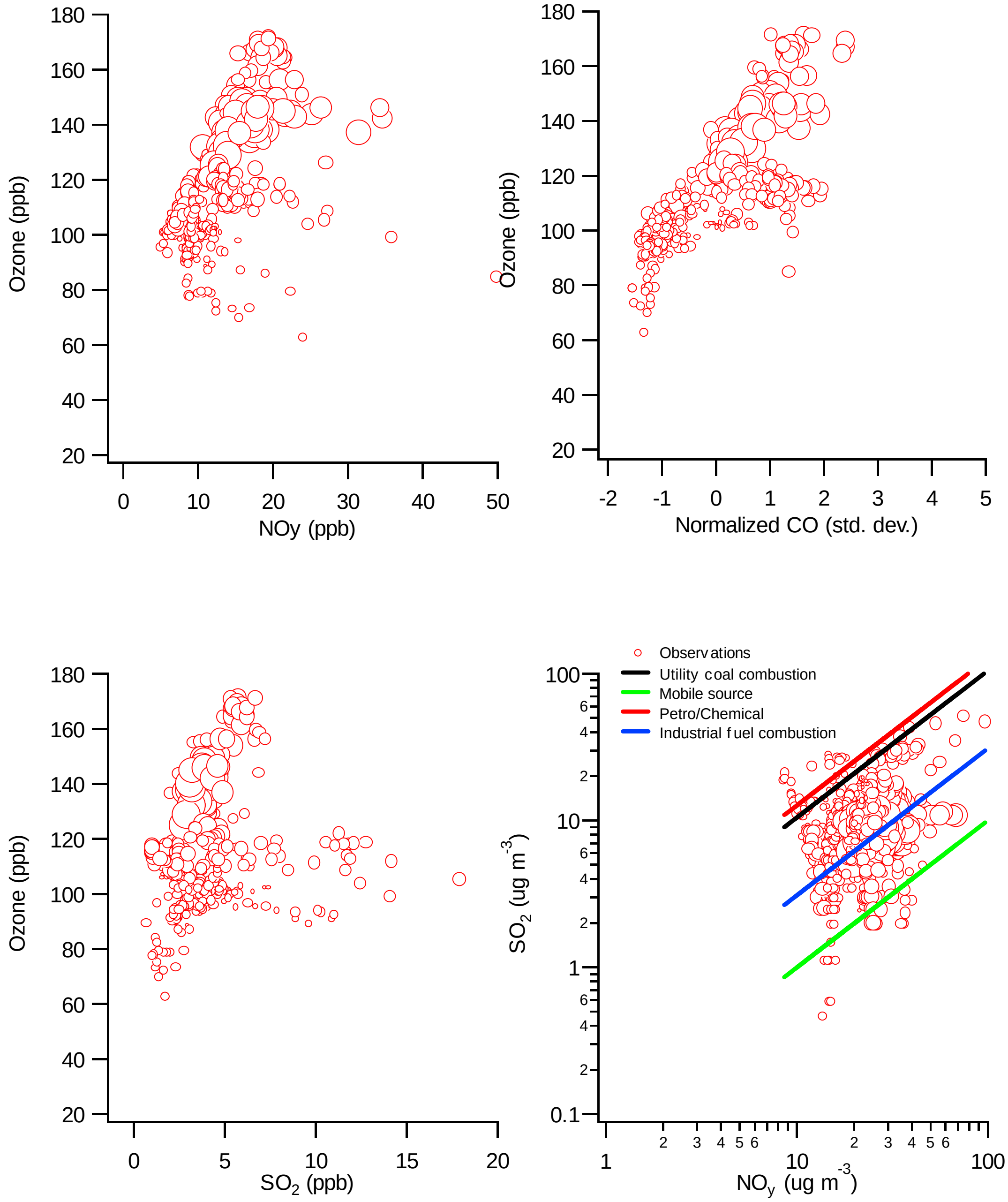




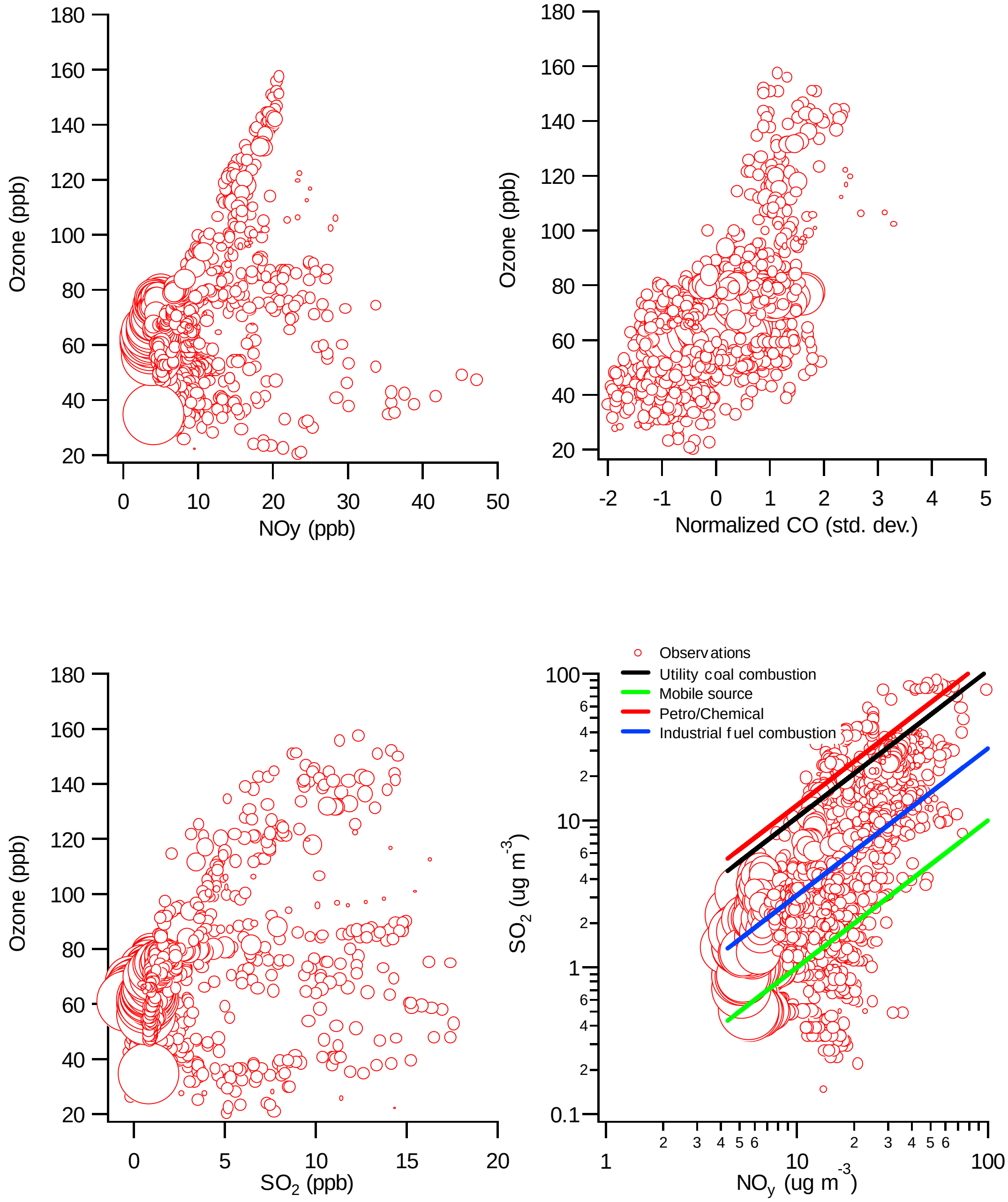
Data file: VCATS000830b.eng



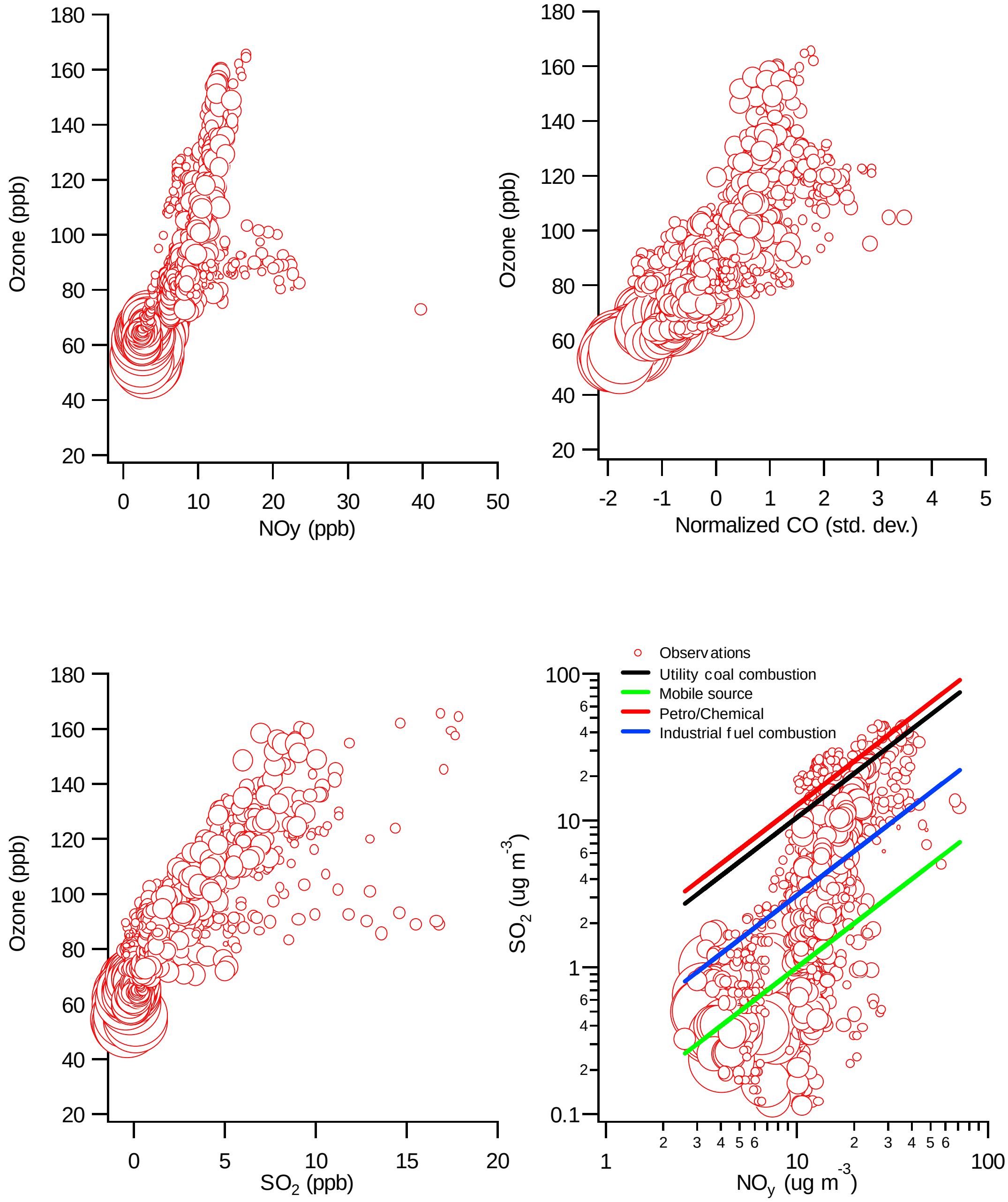
Data file: VCATS000901a.eng



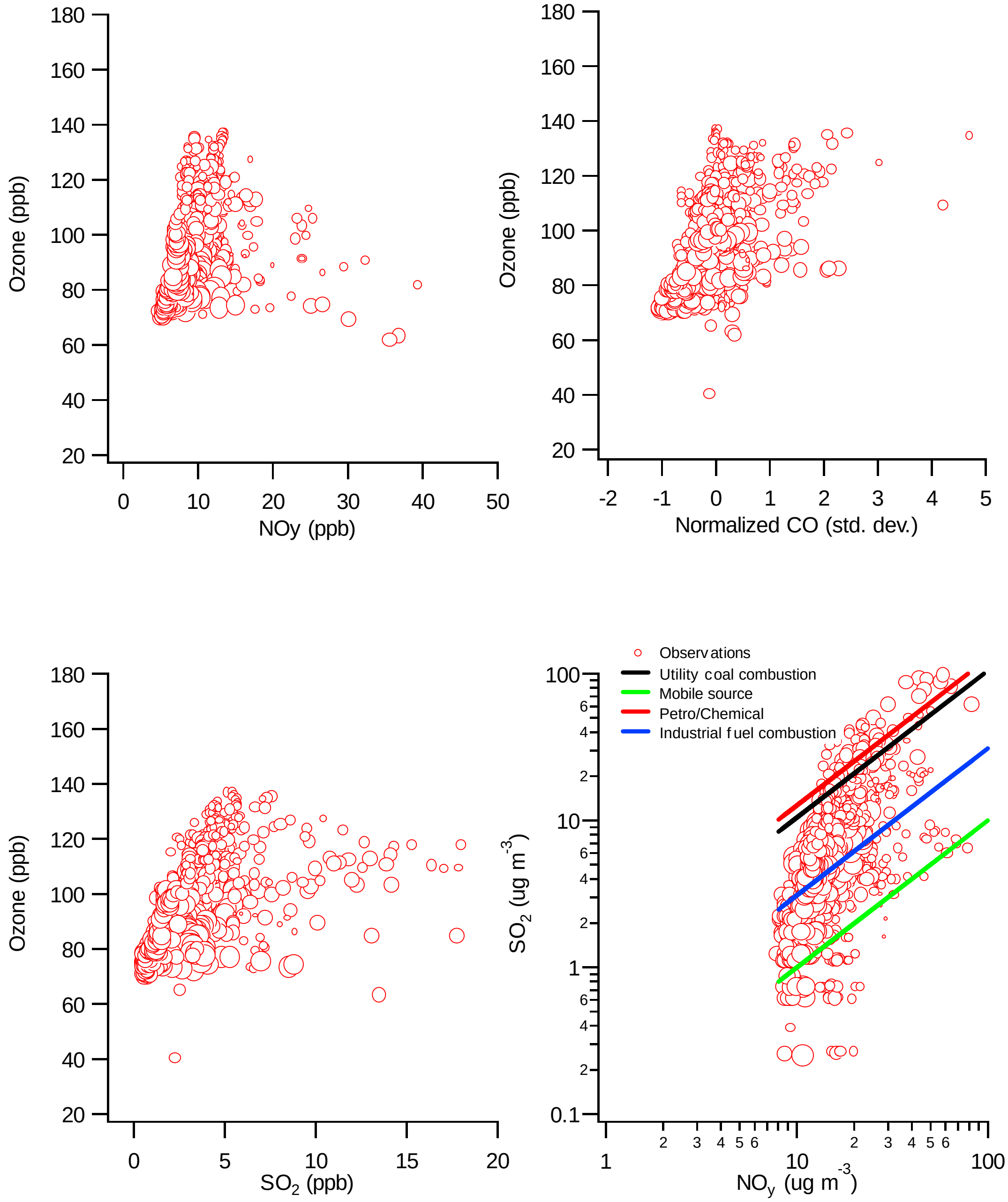
Data file: VCATS000901b.eng



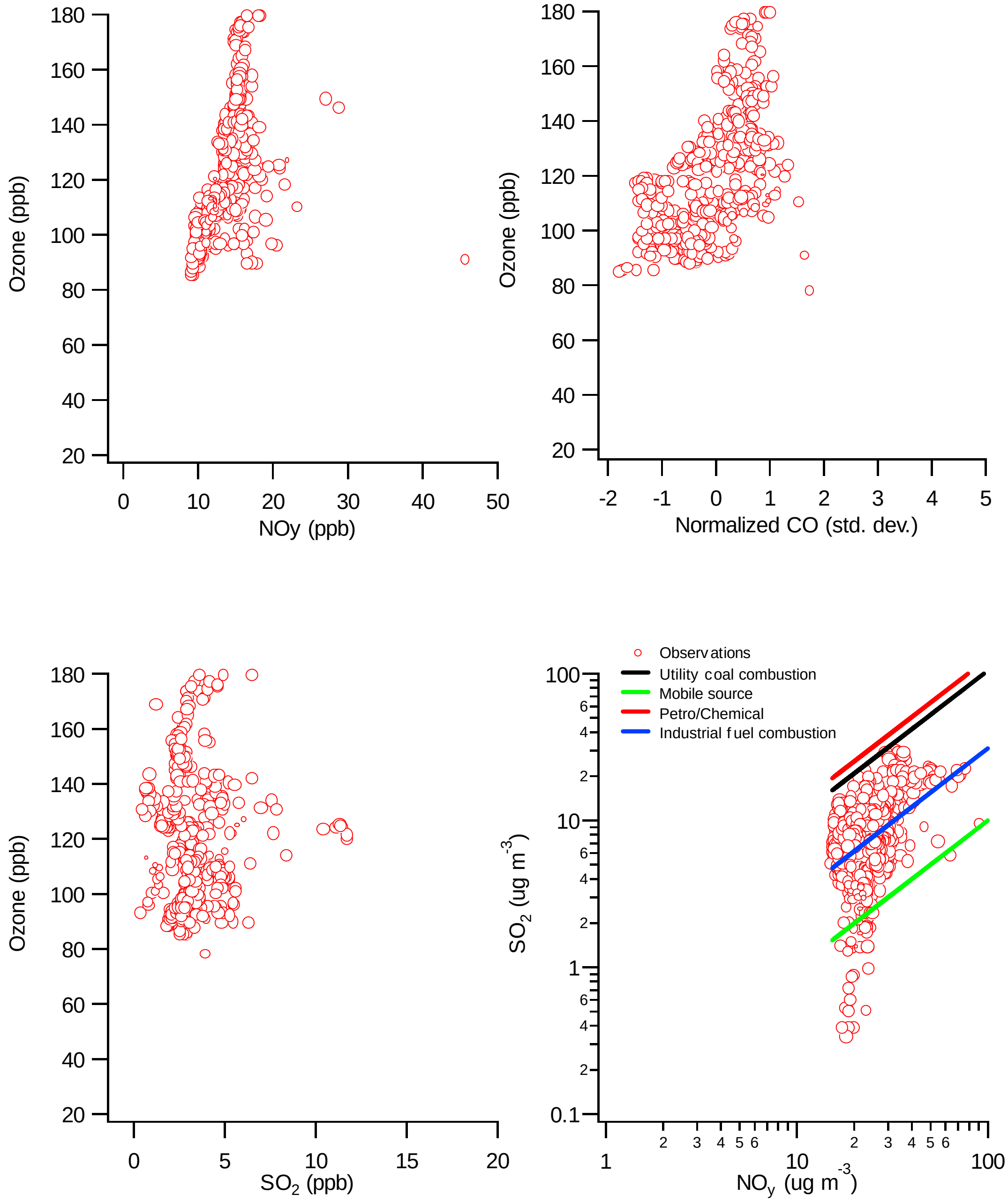
Data file: VCATS000903.eng



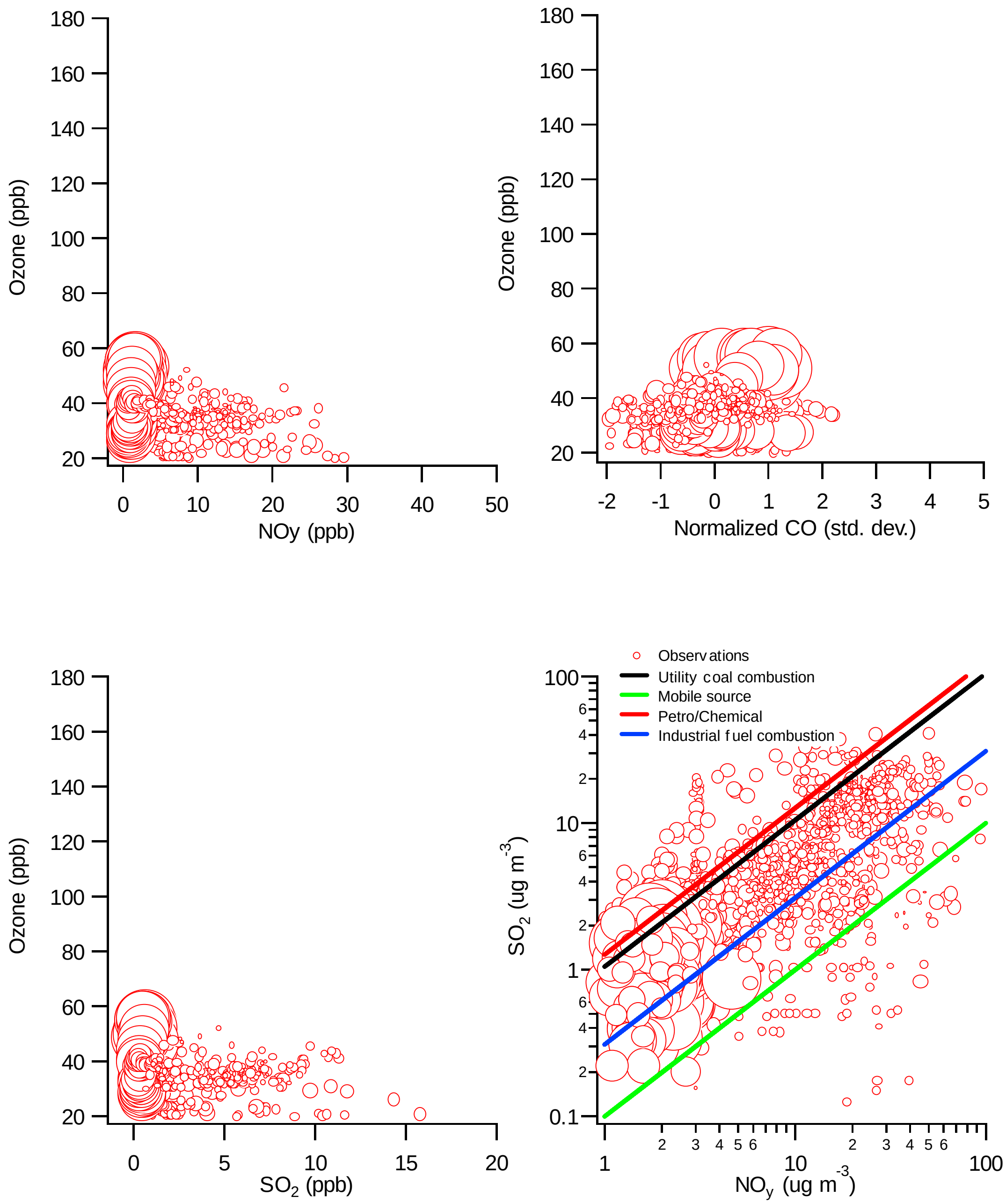
Data file: VCATS000904a.eng



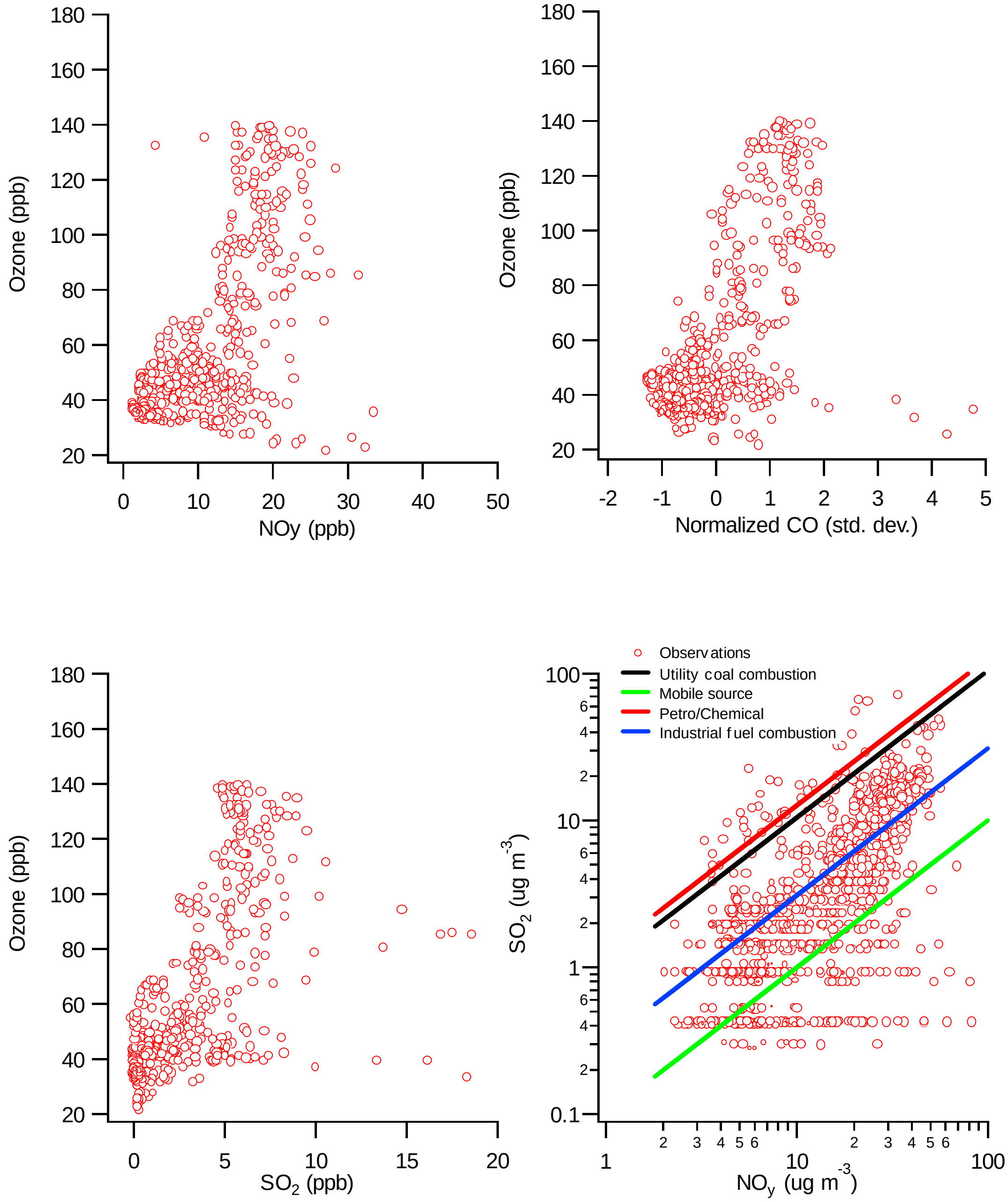
Data file: VCATS000904b.eng



Data file: VCATS000905.eng



Data file: VCATS000912a.eng



Data file: VCATS000912b.eng